the annual report of the nuclear physics laboratory university of washington a.e.c. a.t.[45-1]-1388 june 1968
Frontispiece: the accelerator tunnel and the three-stage FN tandem accelerator.
ANNUAL REPORT

Nuclear Physics Laboratory
University of Washington
June, 1968

Program "A" --
Experimental Nuclear Physics
Program (Cyclotron)
under
U.S. Atomic Energy Commission
Contract A.T.(45-1)-1388
The research reports which follow are intended to describe the status of experiments which in many cases are incomplete. Their appearance here in no way constitutes publication. Specific numerical results and conclusions should not be quoted without permission of the investigators, whose names are given in alphabetical order at the end of each report. Such permission is usually easily obtained and more recent results are cheerfully supplied when available.
This report reviews the research and technical developments conducted at the Nuclear Physics Laboratory of the University of Washington during the year ending June 15, 1968. This work was performed primarily by the faculty and graduate students of the Departments of Physics and Chemistry of the University of Washington, and the staff of the Nuclear Physics Laboratory. Support for these projects is provided by the State of Washington, the U.S. Atomic Energy Commission, and the National Science Foundation. Two of the projects reported involve research originated within the University but outside this laboratory, and their financial support comes from sources other than those which support this laboratory.

The principal facilities of the Nuclear Physics Laboratory are the three-stage FN tandem Van de Graaff accelerator and the 60 inch cyclotron. The injector accelerator was accepted in November and the three-stage tandem has been performing quite satisfactorily since then at proton energies up to 24 MeV. Expansion of secondary facilities this year have included doubling the memory capacity of the SDS 930 on-line computing system, installation of the 90 cm broad-range spectrograph in Tandem Cave I, and construction of a potassium-exchange negative ion source for high intensity 3He and 4He beams.

In the research of the past year there has been continued emphasis on elastic and inelastic scattering, transfer reactions, spin-flip studies, photons from nuclear reactions, compound nucleus studies, and nuclear fission. New sections on analogue states, and computer development and programming have been added which reflect increased activity in these areas. This report also reflects an increased reliance on the tandem accelerators and some slowing of activities on the cyclotron. Nevertheless, the cyclotron remains in active use in many new and continuing research projects and its 43 MeV alpha beam complements the beams available from the tandem.

The verbiage, if not the research volume, has increased this year, as evidenced by this 187-page report as compared with 114 pages last year, for net increase of 64%. Several innovations have been incorporated in this report, notably the cover art, the use of left-side superscripts for isotopes numbers, (e.g., $^{12}$C), a semi-rigorous adherence to the metric system, and the replacement of the Roman numerology of previous reports with the decimal system.

* The National Science Foundation provided the funds to purchase the three-stage tandem Van de Graaff accelerator and some of its associated equipment, and a portion of the funds to construct the laboratory building to house them.
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1. ELASTIC AND INELASTIC SCATTERING

1.1 Elastic and Inelastic Alpha Particle Scattering from $^{12}$C

Excitation functions for the elastic and inelastic (4, 44 MeV) scattering of alpha particles from $^{12}$C have been measured in the laboratory energy range of 21.00 to 23.00 MeV. These measurements were made as a preliminary step in the gamma-ray polarization measurements. The main purpose of this work was to find regions relatively free from scattering resonances that might make the theoretical interpretation of the gamma-ray polarization measurements difficult. As a secondary goal, it was hoped that the measurements might reveal some information about states in $^{16}$O in this region.

Detectors were set at laboratory angles of $20^\circ$, $90^\circ$, $160^\circ$, and $170^\circ$. The target consisted of a 40 μgm/cm² self-supporting carbon foil. The carbon target introduces a 10 keV spread in incident alpha-particle energy. The absolute machine energy calibration error is estimated to be about 20 keV in this energy range. Measurements were made in 10 to 40 keV steps over the 21.00 to 23.00 MeV incident alpha-particle energy range.

The $90^\circ$ and $170^\circ$ elastic and inelastic excitation functions are presented in Figs. 1.1-1 through 1.1-4. Differential cross sections were calculated on the basis of target thickness and may have a 20% systematic error. Statistical errors and errors due to background subtraction are generally less than 3%. Resonances are observed at 21.28, 21.9, and 22.32 MeV incident alpha-particle energies. These resonances correspond to excitation energies of 23.12, 23.6, and 23.90 MeV, respectively, in the $^{16}$O compound nucleus. The widths are about 25, 450, and 30 keV, respectively.

The resonances at 23.6 and 23.90 MeV excitation energy in $^{16}$O have been observed in other $^{12}$C($α,α$) work and $^{14}$N($d,α$) work. Resonances have been observed at 23.1 MeV excitation in $^{16}$O($γ,N$), $^{15}$N($p,γ$), and $^{16}$O($γ,p$) reactions. We hope soon to determine the spins of these states by a more careful study of the angular distributions. (J. Eonmaa, T.D. Hayward, R.H. Lewis, D.M. Patterson, F.H. Schmidt, and J.R. Tesmer)

1. Section 5.1 of this report (Gamma Polarization).
2. John H. Williams Laboratory of Nuclear Physics Annual Report, University of Minnesota (1967), p.3.
Fig. 1.1-1. Excitation Function for the Elastic Scattering of Alpha-Particles from $^{12}$C at a Lab Angle of 90°.

Fig. 1.1-2. Excitation Function for the Inelastic (4.44 MeV) Scattering of Alpha-Particles from $^{12}$C at a Lab Angle of 90°.

Fig. 1.1-3. Excitation Function for the Elastic Scattering of Alpha-Particles from $^{12}$C at a Lab Angle of 170°.

Fig. 1.1-4. Excitation Function for the Inelastic (4.44 MeV) Scattering of Alpha-Particles from $^{12}$C at a Lab Angle of 170°.
1.2 $^{12}\text{C}(\alpha,\alpha')\gamma$ Angular Correlation

The in-plane angular correlation for the $^{12}\text{C}(\alpha,\alpha')\gamma$ reaction has been measured at 35 alpha-particle scattering angles between 150° and 165° (laboratory angles). At each alpha-particle scattering angle correlations were measured at six gamma angles between 25° and 150°. A gamma detector of known efficiency\(^1\) was used so that the $m = 0$ substrate population as well as the $m = \pm 2$ substrate parameters could be extracted. The incident beam energy was 22.750 MeV. It was chosen from results of the $^{12}\text{C}$ excitation study\(^2\) to lie in a region as well removed from resonances as possible. The target was a self-supporting 197 µg/cm\(^2\) carbon foil (approximately 50 keV thick to the incident beam). The data is as yet unanalyzed. The results of the analysis will indicate the alpha scattering angles at which the nuclear polarization, and hence the gamma-ray circular polarization, is large. The sense of that polarization will then be determined by the circular polarization experiment.\(^3\)

The new He\(^+\) ion source\(^4\) was used for these measurements. Beams of 50 to 800 nA were produced as desired with relative ease. Total running time was four days. (J. Benmaa, T.D. Hayward, R.H. Lewis, D.M. Patterson and J.R. Tesmer)

1. Section 10.3 of this report (γ-counter calibration).
2. Section 1.1 of this report ($^{12}$C excitation function).
3. Section 5.1 of this report (polarization measurement).
4. Section 12.7 of this report (He\(^+\) ion source).

1.3 Elastic Scattering of Alpha Particles from Intermediate Mass Nuclei and the Isotopic Dependence of Nuclear Radii

An account was given in the 1967 Annual Report\(^5\) of measurements of elastic scattering of 42 MeV alpha particles from Ca isotopes. By employing a very tight geometry and by monitoring repeatedly the energy variations of the beam, we were able to make rather precise comparisons of the angular distributions from these nuclei and thereby detect small isotopic shifts in the strong absorption radii. These measurements have now been extended to other intermediate mass nuclei, specifically $^{46,48,50}$Ti, $^{52}$Cr, $^{54,56}$Fe, and

Fig. 1.3-1. Differential cross sections for the elastic scattering of 42 MeV alpha particles from $^{46,48,50}$Ti and $^{52}$Cr near 35°. The curves are drawn to guide the eye and are not theoretical.
58, 60, 52\text{Ni}. In addition, the energy dependence of the angular distributions from $^{40}\text{Ca}$, $^{50}\text{Ti}$, and $^{62}\text{Ni}$ have been checked at the degraded beam energies, 40.9 and 39.5 MeV.

The experimental arrangement described in last year's report was again used in the extended measurements. As before, considerable attention was given to the minima in the angular distributions near 33°. As an example, the cross sections of $^{46,48,50}\text{Ti}$ and $^{52}\text{Cr}$ in this region are shown in Fig. 1.3-1.

Again, the data have been analyzed in terms of three models. (1) The location of the minimum near 33° alone is used to obtain $R_{\text{FC}}$, the Coulomb corrected radius of the Fruanhofer black nucleus model. (2) A scattering amplitudes parametrization containing three parameters\textsuperscript{2} has been employed to define several varieties of strong absorption radii, the most important being $R_{\text{F}} \frac{1}{2}$, which is directly related to the critical angular momentum parameter, L. (3) The scattering amplitudes resulting from analysis with a traditional four parameter complex Wood-Saxon potential also may be used to define analogous strong absorption radii.

As an example of the quality of the theoretical fits obtained, we show in Fig. 1.3-2 the observed angular distributions from $^{44}\text{Ca}$ together with the best optical model fit (solid line) and the best fit with scattering amplitudes parametrization (dashed curve). It has been found that all depths of the real optical potential greater than 70 MeV gave indistinguishable fits to our data; accordingly, a standard depth of 200 MeV was adopted for all isotopes. The

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\textbf{Fig. 1.3-2.} Observed differential cross section for elastic scattering of 42 MeV alpha particles from $^{44}\text{Ca}$ together with the best optical model fit (solid curve) and the best fit with scattering amplitudes parametrization (dashed curve).
other model parameters corresponding to Fig. 1.3-2 are: \( W = 40.69 \) MeV, \( R_{opt} = 4.927 \) F, and \( a = 0.573 \) F; the three parameters of the scattering amplitudes are \( L = 16.599 \), \( \Lambda = 0.889 \) and \( \alpha = 1.265 \).

The results of the study are most concisely summarized in Fig. 1.3-3 where we plot versus \( A^{1/3} \) the Coulomb corrected strong absorption radius of the Fraunhofer model, \( R_C \), the strong absorption radius of the optical model corresponding to the real part of the partial wave amplitude equalling 1/2, \( R_{1/2} \), and the similar strong absorption radius of the direct parametrization, \( R_D 1/2 \). It is seen that all three methods lead to similar values of radii; more important, each variety of radius shows a similar isotopic dependence.

Concerning the isotopic variations, our main conclusions are:

1. With one conspicuous exception, the strong absorption radii increase monotonically with \( A^{1/3} \).
2. On the other hand, the slopes at the lines joining corresponding radii of neighboring isotopes are not constant throughout the region. When the slopes, \( R / (A^{1/3}) \), are characterized by the parameter \( r_0 \), we find between \( ^{40}\text{Ca} \) and \( ^{44}\text{Ca} \) that \( r_0 \) is in the range 0.6 to 0.9 F. On the other hand, between \( ^{56}\text{Ni} \) and \( ^{62}\text{Ni} \), we find that \( r_0 \) lies between 1.9 and 2.0 F. In contrast, the slopes of the lines joining corresponding radii of \( ^{62}\text{Ni} \) and \( ^{40}\text{Ca} \) lie between 1.17 and 1.36 F.
3. The values of the radii for \( ^{48}\text{Ca} \) appear to be anomalously low when compared with corresponding radii in the neighboring isotopes.
4. Further, our study of scattering at 40.9 and 39.5 MeV revealed no energy dependence in the values of strong absorption radii. (J.S. Blair and B. Fernandez)

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1.4 Inelastic Scattering of Alpha Particles from \( ^{39}\text{K} \) and \( ^{51}\text{V} \)

As a continuation of the study of inelastic scattering of \( 4.2 \) MeV alpha particles by intermediate mass nuclei discussed in the 1965 Annual Report, an extensive analysis of scattering from \( ^{39}\text{K} \) and \( ^{51}\text{V} \) has been completed and a paper prepared for publication. The salient conclusions of this study are the following: (1) For some
levels of $^{39}$K, a satisfactory description is furnished by a weak coupling model, according to which the $d_3/2$ proton hole ground state is coupled to the strong octupole excitation of the $^{40}$Ca core. In particular, the 3.60 MeV and 3.90 MeV states are assigned spin-parities $9/2^-$ and $7/2^-$ while the spin-parities $3/2^-$ and $5/2^-$ are suggested for two states near 4.14 MeV. (2) The weaker excitation found for levels at 2.59, 2.85, and 3.02 MeV is consistent with their presumed single particle character and the spin-parity assignments $l/2^+$, $7/2^-$, and $3/2^-$, respectively, although there is a suggestion that there is collective octupole enhancement of the last level. (3) The quadrupole weak-coupling prediction for the low-lying levels of $^{39}$K did not agree at all well with the data. On the other hand, a good fit is obtained with the shell model predictions within a $(f_{7/2})^3$ proton hole configuration if further the quadrupole excitation is enhanced relative to the hexadecapole cross section by a factor of four.

(R.J. Peterson)

2. R.J. Peterson (submitted for publication).

1.5 Elastic and Inelastic Scattering of 42 MeV $\alpha$ Particles from $^{87}$Rb

The study of elastic and inelastic scattering of 42 MeV $\alpha$ particles from $^{87}$Rb reported last year\(^1\) was continued. An attempt to fabricate a metallic Rb target by a process similar to that described\(^2\) for Ca and Sr was abandoned, as the targets prepared in this way were about two orders of magnitude too thin. Similarly, an attempt to electrospray\(^3\) RbCO$_3$ targets was abandoned when the targets proved to be granular and to contain fairly large amounts of Na, Si, and Cl impurities. Usable targets were obtained by vacuum evaporation of RbNO$_3$. The nitrate was formed by the conversion of RbCl (enriched to 99% $^{87}$Rb)\(^4\) in nitric acid. The solution was then heated to dryness and the resulting RbNO$_3$ placed in a platinum boat and vacuum evaporated on a 50 $\mu$g/cm$^2$ carbon backing.

The 42 MeV $\alpha$ particles scattered from these targets were detected in 1000 $\mu$ Si(Li) detectors.\(^5\) One of these

![Fig. 1.5-1. Spectra of 42 MeV alpha-particles scattered from $^{87}$Rb. The excitation energies of the states of $^{87}$Rb are listed above their respective peaks.](image)
detectors was set at a maximum in the angular distribution for elastically scattered α particles from Rb and was used as a monitor. The spectrum from this monitor was analyzed in the same manner as that from the movable detector, providing an accurate check on the target uniformity.

Two energy spectra (corresponding to a maximum and minimum in the elastic angular distribution) are shown in Fig. 1.5-1. The energy resolution is about 130 keV (FWHM). Peaks were seen and kinematically identified as arising from states of 87Rb at excitation energies of 0.40 ± 0.15, 0.84 ± 0.15, 1.43 ± 0.03, 1.76 ± 0.15, 2.01 ± 0.15, 2.22 ± 0.15, 2.40 ± 0.02, and 2.76 ± 0.02 MeV. Other peaks corresponding to states above 3 MeV were also seen but could not be consistently identified. The peak at 1.43 MeV seems to be wider than the other peaks in the spectra, indicating the possible existence of more than one state close to this energy. A weak peak was also seen occasionally at about 2.59 MeV but could not be positively identified.

Data were taken for elastic scattering from 20° to 54° in 1° intervals and in 2° intervals to 65°. Angular distributions were obtained for the excitation of states of 87Rb only in the angular region where the peaks corresponding to these states were higher in energy than the elastic peak for the oxygen impurity.

A slight Si impurity was noticed in the target. Corrections for this impurity were made using 28Si(α,α) elastic scattering data.7

The thickness of the RbNO3 target could not be accurately obtained by direct weighing. Attempts to obtain absolute cross sections by comparing the yields of elastically scattered α particles from the 16O and 14N portions of the nitrate to measured 16O(α,α)8 and 14N(α,α)9 elastic cross sections proved unreliable because of the energy variations of these elastic cross sections.8 The absolute cross sections were obtained by normalizing the elastic cross section to an optical model calculation10 in the region 20° to 25°. It was found that the optical model predictions at these angles were quite insensitive to the parameters used in the calculations. The uncertainty in the absolute cross sections obtained in this way is estimated to be about ±10%.

The fit to the elastic scattering data obtained from the optical

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Fig. 1.5-2. Ratio of elastic differential cross section to Rutherford cross section compared with optical model calculation. The parameters for the optical model are listed on the figure.
model analysis is shown in Fig. 1.5-2. The optical model parameters obtained from this calculation are listed on the figure. The angular distributions for inelastic scattering were analyzed using the DWBA code TSALLY.11 This analysis is complicated by the fact that the ground-state spin of $^{87}$Rb is $3/2$. This allows two values of orbital angular momentum transfer for each transition. The contribution of each multipolarity will be proportional to the reduced matrix element of the appropriate interaction potential between the initial and final states. In keeping with the ideas of the collective model, it will be assumed that the most important contributions will come from multiplicities $I = 2$ for
parity-conserving transitions and $I = 3$ for parity-changing transitions.

The angular distributions for the transitions to states at 0.40, 0.84, 1.43, 1.76, 2.01 and 2.22 MeV, which are out of phase with the elastic angular distribution, are shown in Fig. 1.5-3, along with the DWBA predictions for the $I = 2$ transitions. The angular distributions for the transitions to the states at 2.40 and 2.76 MeV, which are in phase with the elastic angular distribution, are compared to the DWBA predictions for $I = 3$ in Fig. 1.5-4.

The strengths of these transitions can be characterized by the partial deformation length $^{12} \beta_{IR}^p$ which is defined by the relation

$$\frac{d\sigma}{d\Omega}_{\text{exp}} \propto (\beta_{IR}^p)^2 \sigma_{\text{DW}}(\theta)$$

where $\sigma_{\text{DW}}$ is the output of the DWBA theory. The values of $(\beta_{IR}^p)^2$ are listed in Table 1.5-1 along with the strength of the transition in single-particle units obtained from the formula$^{13,14}$

![Graphs showing angular distributions](image)

**Fig. 1.5-4.** Differential cross sections for the excitation of the 2.40$^-$ and 2.76$^-$ MeV states of $^{87}$Rb compared with the DWBA $I = 3$ predictions.


\[ G_I = \frac{Z^2(\beta^P_{IR})^2 (3 + 1)}{4\pi R_{cm}^2 (2I + 1)} \]

(1)

where \( Z \) is the charge of the target, \( I \) is the orbital angular momentum transfer and \( R_{cm} \) is the electromagnetic radius.

Table 1.5-1. Spectroscopic information extracted from the present experiment. Column 1 lists the excitation energies and their uncertainties. Column 2 gives the parities, columns 3 and 4 list the values of the partial deformation lengths and column 5 gives the transition strength in single particle units obtained from the formula in the text.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Excitation Energy (MeV)} & \text{Parity} & (\beta^P_{IR})^2 & \beta^P_{IR} & \beta^P_{IR} & G_I \\
\hline
0.40 \pm 15 & - & 0.031 & 0.18 & 0.6 \\
0.94 \pm 15 & (-) & 0.01^a & 0.1^a & 0.2^a \\
1.63 \pm 15 & - & 0.058 & 0.24 & 1.1 \\
1.76 \pm 15 & - & 0.10 & 0.31 & 2.0 \\
2.01 \pm 15 & - & 0.042 & 0.20 & 0.8 \\
2.24 \pm 20 & - & 0.066 & 0.26 & 1.3 \\
2.40 \pm 20 & + & 0.157 & 0.40 & 3.1 \\
2.59 \pm 40 & (-) & - & - & - \\
2.76 \pm 20 & + & 0.132 & 0.36 & 2.6 \\
\hline
\end{array}
\]

a. Upper limit only.

b. Possibly a doublet.

A level diagram of the energies and parities of the states determined in the present experiment is compared with the previously known states of $^{87}$Rb and with the states of $^{88}$Sr in Fig. 1.5-5. The presence of four negative parity states centered around the energy of the 1.84 MeV (2⁺) state of $^{88}$Sr is suggestive of the weak coupling model. The ratio of the inelastic scattering strengths to the individual states of $^{87}$Rb and the total strength for these states are not consistent with the weak-coupling core-excitation model. However, the total strength of these states is only about 70% of the strength of the excitation of the 1.84 MeV (2⁺) state of $^{88}$Sr. Also, as was pointed out before, there may be more than one state at about 1.43 MeV.

In presence of negative parity states at rather low excitation energies may explain the small spectroscopic factors reported for the $^{88}$Sr(d, 3He) reaction leading to the ground and first excited states of $^{87}$Rb. If the spins of
some of these low-lying negative parity states are $3/2$ or $5/2$, then there may be mixing in the ground and first excited states of $^{87}$Rb.

It would be of particular interest to study the states of $^{87}$Rb with improved energy resolution. The present experiment may have missed closely-spaced levels that could be seen with improved resolution. The energies and parities assigned in this work cannot be regarded as firm until such a study is made. (D.C. Shreve)

Fig. 1.5-5. Energy level diagram of the states of $^{87}$Rb compared with the previously known energy levels of $^{87}$Rb and the states of $^{88}$Sr.

4. Obtained from Oak Ridge National Laboratory, Isotope Sales Division.
5. The Li-drift detectors were fabricated at this laboratory.
8. N. Cue, Private communication.
10. The optical model program used was OP, written by B. Fernandez of this laboratory.
19. C.D. Kavaloski, J.S. Lilley, D.C. Shreve and N. Stein, Phys. Rev. 161, 1107 (1967); see also Sec. 2.8 of this report.
1.6 Elastic Scattering of 21 MeV Deuterons from $^{89}$Y and $^{90}$Zr

The elastic scattering of 21 MeV deuterons from $^{89}$Y and $^{90}$Zr has been measured. This experiment was undertaken in an effort to obtain better optical model parameters for the analysis of the (d, $^3$He) studies on $^{90}$Zr, $^{89}$Y and $^{88}$Sr.\(^1\) The elastically scattered deuterons were identified using a \(\Delta E-E\) counter telescope which consisted of a 300 \(\mu\) \(\Delta E\) detector and a 2000 \(\mu\) E detector. Differential cross sections were obtained in 1° intervals from 12° to 50° and in 2° intervals from 50° to 100°. The angular distributions were fitted using a spin-independent optical model search.\(^2\) Figure 1.6-1 compares the ratio \(d/d_R\) for $^{89}$Y (the ratio of elastic differential cross section to the Rutherford cross section) to the results of spin-independent search and to the results of a spin-dependent calculation\(^3\) using the parameters of Perey and Perey\(^4\) (obtained from the analysis of 25 MeV deuterons on $^{90}$Zr). The parameters for these calculations are listed in Table 1.6-1. (The experimental angular distributions for $^{90}$Zr(d,d) and $^{89}$Y(d,d) were almost identical and only the fit to one is shown.) It is seen that the fit obtained from the spin-independent search is better at forward angles. The spin dependent calculation agrees with the data quite well except at the first two minima. Better spin dependent fits probably could have been obtained if an automatic search had been used. (D.C. Shreve)

### Table 1.6-1. Optical model parameters for 21 MeV deuterons incident on $^{89}$Y.

The parameters for Set 1 were obtained using a spin independent optical model search with the starting parameters of Ref. 1. The parameters for Set 2 were obtained from Ref. 4. The form of the optical model potential is the same as that used in Sec. 2.6 of this report.

<table>
<thead>
<tr>
<th>Spin Independent Search</th>
<th>V (MeV)</th>
<th>W (MeV)</th>
<th>$W'$ (MeV)</th>
<th>$V_{80}$ (MeV)</th>
<th>(r) (F)</th>
<th>(V_{T}) (F)</th>
<th>(a) (F)</th>
<th>(a_T) (F)</th>
<th>(r_0) (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference 4</td>
<td>100.8</td>
<td>0</td>
<td>52.56</td>
<td>3.26</td>
<td>1.099</td>
<td>1.349</td>
<td>0.835</td>
<td>0.747</td>
<td>1.3</td>
</tr>
</tbody>
</table>

![Fig. 1.6-1. Ratio of elastic differential cross section for scattering of 21 MeV deuterons from $^{89}$Y to Rutherford cross section compared with optical model predictions. The solid curve is the result of a spin-independent local optical model search. The dashed curve is the result of a spin-dependent optical model calculation using the parameters of Ref. 4.](image-url)
1. C.D. Kavaloski, J.S. Lilley, D.C. Shreve and N. Stein, Phys. Rev. 161, 1107 (1967); also see Sec. 2.8 of this report.

2. The optical model program used was TOP, written by B. Fernandez, Nuclear Physics Laboratory Annual Report, University of Washington (1967), p. 34.

3. The spin-dependent elastic cross sections were obtained from the DWBA code DWUCK written by F. Kunz, University of Colorado (1967).


1.7 Direct Reaction α-Particles from Heavy Nuclei Bombarded by 42, 50, 65, 90 MeV α-Particles

In last year's progress report I a set of measurements on the inelastic scattering of α-particles from heavy nuclei was briefly mentioned. These measurements were carried out at incident energies of 42, 50, 65 and 90 MeV at the Berkeley 88-inch cyclotron. At each of these energies full α-particle spectra were recorded at roughly every 20°. The targets studied were tantalum, gold and lead.

In the forward hemisphere the observed differential cross-sections,

$$\frac{d^2\sigma}{dE\,d\Omega},$$

(a) increased rapidly with decreasing angle up until the most forward angles (≈25°) at which observations could be safely made, (b) dropped off sharply for values of $E_\alpha$ below the α-particle Coulomb barrier, (c) increased at a given angle and energy with increasing mass number A of the target, and (d) showed very little gross-structure at energies corresponding to excitations in the residual nucleus above 10 MeV.

Some preliminary work has been done in comparing the observations with conventional models for angular distributions in the inelastic scattering of α-particles. These comparisons, which make use of a DWBA computer code, are made difficult by the large number of partial waves (up to $l=50$) which must be used. Because of the energy mismatch between incoming α particles and the lowest energy outgoing particles, one must consider angular momentum transfers, $\Delta l$, up to relatively high values. So far only $\Delta l$ values up to 8 have been studied, but these computations already show a measure of qualitative agreement with the observed angular distributions. Further work must be done on extending the range of the DWBA calculations, on examining the sensitivity of results to choices of optical model parameters and on the development of a model to account for the observed energy distributions. An interesting by-product of these studies was the identification and measurement of evaporated α particles in the backward hemisphere. This is discussed in Sec. 6.5 of this report. (G. Chenevert and I Halpern)
2. P. D. Kunz, DWBA code DWUCK (University of Colorado).
2. NUCLEON TRANSFER AND CHARGE EXCHANGE REACTIONS

2.1 Search for Singlet Deuterons in the $^{12}$C($a$,d)$^{14}$N Reactions

In a recent investigation of the reaction $^9$Be(p,pn)$^8$Be, Cohen, May and O'Keeffe\(^1\) have observed a correlation between the proton and neutron emission angles and energies which they interpret as the pickup of a neutron by the incident proton to form deuterons in the virtual 0\(^+_1\), T = 1 singlet excited state of deuterium which is unbound by about 40 keV.\(^2\) This conclusion is primarily based on indirect evidence; in particular, the correlation in angle and energy of the proton and neutron, and the similarity in cross section and angular distribution between this reaction and the (p,4) reaction on the same target. Tenmer\(^3\) in an earlier paper discussed evidence for singlet deuteron formation on the basis of data from the $^{13}$C(p,n) reaction at 0\(^0\).

We have attempted to observe singlet deuterons produced in the two-nucleon stripping reaction $^{12}$C($a$,pn)$^{14}$N. Such a reaction we will call ($a$,d) where d signifies a deuteron in the virtual singlet state.\(^1\) Since the target and the incident particle are both T = 0, isospin conservation requires that triplet deuterons (1\(^+_1\), T = 0) will populate only T = 0 states in $^{14}$N, and singlet deuterons (0\(^+_1\), T = 1) will populate only T = 1 states.\(^4,5\) Thus the observation of protons and neutrons closely correlated in angle and energy and populating the first excited state but not the ground state of $^{14}$N in the $^{12}$C($a$,pn)$^{14}$N reaction would be clear and direct evidence of the production of singlet deuterons in this reaction, while population of the $^{14}$N ground state might suggest the breakup of triplet deuterons by the nuclear and Coulomb fields on their way out of the nucleus.

This reaction has several advantages from the viewpoint of the expected strength of the reaction over the (p,pn) reaction. First the 1/(2S + 1) statistical factor in the latter reaction is absent in ($a$,pn). Second, the strength of a singlet-even component of the nucleon-nucleon force determines the strength of the neutron pickup in the (p,d) reaction, while the triplet-even strength dominates in a singlet two-particle transfer reaction like ($a$,d). Since the triplet-even strength appears to be about twice the singlet-even strength in the Hamada-Johnston potential, there should be an enhancement factor in ($a$,d), while there should be a comparable de-enhancement in (p,d). This might account for the factor of 4 between the (p,d) and (p,4) yields in the Cohen experiment\(^1\) which is left after correction for phase space effects and (2S + 1) factors.

Our study of this reaction with geometry similar to that of Cohen\(^1\) has yielded negative results which imply a singlet deuteron yield which is less than would be expected on the basis of the above arguments. Further work is planned to either definitely observe the singlet deuterons or set a meaningful upper limit on their production. (W.J. Braithwaite, J.G. Cramer, W.W. Eidson, and F.W. Slee)

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2.2 Study of the $^{14}\text{N}(d,p)^{15}\text{N}$ Reaction and States in $^{15}\text{N}$

The level structures of the mirror nuclei, $^{15}\text{N}$ and $^{15}\text{O}$, have been of considerable theoretical interest because they are just one nucleon short of filling the $1p$ shell. In fact, the $1/2^-$ ground state and $3/2^-$ level at 6.32 MeV in $^{15}\text{N}$ have been represented as a $1p_{1/2}$ and $1p_{3/2}$ hole, respectively. The additional low-lying levels have unnatural (positive) parity and must involve $2s$ and $1d$ shell configurations or a $1s_{1/2}$ hole. Independent Particle Model (IPM) calculations have been generally successful in describing the level structure up to about 9 MeV in excitation in $^{15}\text{N}$ but fail to reproduce the complexity of levels above 9 MeV.\footnote{2} It is in precisely this region that the experimental picture also becomes unclear.

The 9.05 MeV level has been established as either $1/2^+$ or $3/2^+$ and is probably $1/2^+$ based on a comparison of experimental gamma-ray branching ratios and the IPM predictions.\footnote{3,4} The widely varying branching ratios which have been observed at 9.16 MeV for different reactions has led to the conclusion that there is a close-lying unresolved doublet at this excitation energy.\footnote{4,5} One of these (9.16a) decays strongly to the ground state and has spin $3/2$ based on a gamma-ray angular correlation measurement.\footnote{4} The other (9.16b) decays weakly, if at all, to the ground state and has a strong branch to the $5/2^+$ level at 7.15 MeV. The 9.22 MeV state is probably spin $3/2$.\footnote{4} The corresponding region in $^{15}\text{O}$ has been studied by the $^{14}\text{N}(p,γ)^{15}\text{O}$ reaction.\footnote{6} A $1/2^+$ level at 8.75 MeV and spin 3.2 levels at 8.92 and 8.98 MeV have been observed. On the basis of similar gamma-ray branching ratios these have been tentatively identified as analogues of the 9.05, 9.22, and 9.16a levels, respectively, in $^{15}\text{N}$. On this basis the 8.92 MeV $^{15}\text{O}$ level could equally be identified as the analogue of 9.16b, since the $5/2^+$, 6.86 MeV level and the $3/2^+$, 6.79 MeV level were unresolved in the gamma-ray measurements on $^{15}\text{O}$. In either case, the hypothesis of a 9.16 MeV doublet in $^{15}\text{N}$ requires a fourth

![Fig. 2.2-1. $^{14}\text{N}(d,p)^{15}\text{N}$ Proton Energy Spectrum at 30° and 8 MeV Incident Energy.](image-url)
Table 2.2-1. Optical Model Parameters Used in the DWBA Calculations.

<table>
<thead>
<tr>
<th></th>
<th>TSALLY</th>
<th>DWUCK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d</td>
<td>p</td>
</tr>
<tr>
<td>V (MeV)</td>
<td>87.4</td>
<td>48.30</td>
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<td>R₀ (F)</td>
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<tr>
<td>a (F)</td>
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<td>0.64</td>
</tr>
<tr>
<td>W (MeV)</td>
<td>20.0 (srf)</td>
<td>7.00 (srf)</td>
</tr>
<tr>
<td>R₀₁ (F)</td>
<td>1.4</td>
<td>1.25</td>
</tr>
<tr>
<td>a₁ (F)</td>
<td>0.7</td>
<td>0.47</td>
</tr>
<tr>
<td>V₀0 (MeV)</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>


level, which has not been observed in this region of $^{15}O$, if the one-to-one correspondence of mirror levels is to be preserved. Due to the large nonresonant background in the $^{14}N(p,γ)^{15}O$ experiment and the likelihood that the fourth level may lie close to one of the three known levels, an additional level in this region could easily have been missed.

We have undertaken a study of the reaction $^{14}N(d, p)^{15}N$ at incident deuteron energies of 7.0, 8.0 and 9.0 MeV using targets of Adenine (C₉H₇N₅) deposited on thin gold foils. Particles were detected by a 50 micron transmission detector and a 1000 micron detector mounted in a $ΔE, E$ configuration. A conventional multiplier circuit was used for particle identification. Figure 2.2-1 shows the energy spectra ($E + ΔE$) of protons at 30° laboratory angle and 8 MeV incident energy. Angular distributions were obtained from about 20° to 60° and Distorted Wave Born Approximation (DWBA) fits have been obtained, with and without a spin-orbit potential, using the

Fig. 2.2-2. Proton Angular Distributions of $^{15}N$ Levels Used in DWBA Fit.
parameters given in Table 2.2-1. Figure 2.2-2 shows the results for levels at 6.32, 7.15, 7.30 and 7.56 MeV in $^{15}\text{N}$. Included in the fits is the compound-nucleus contribution obtained by a Hauser-Feshbach calculation normalized to fit the relatively small cross-section 6.32 MeV angular distributions at large angles. The same normalization was then used for all other levels. It was then assumed that these parameters could be used to try to obtain fits to the 9.16 and 9.22 MeV levels. (The 9.05 MeV level was obscured by protons from $^{12}\text{C}$.) Preliminary results are shown in Fig. 2.2-3. The small angle data has large uncertainties due to background from deuterons which leaked through the identification system. It is now believed that this was an electronics problem and we hope to improve the statistics in this region. Since the target nucleus, $^{14}\text{N}$, has spin 1, there is a possibility of mixed $\lambda$-values (orbital angular momentum transfer) for a given final state spin. For sharp parity, however, the $\lambda$-values must be either even (+) or odd (−). With this in mind, the 9.22 MeV angular distributions are best fit by $\lambda = 1$ and possibly a small $\lambda = 3$ contribution, but not well by $\lambda = 0$ and 2. This implies negative parity. The possibility of mixed parity in the 9.16 MeV doublet, allows both even and odd $\lambda$-values, which appear to be necessary in order to fit the data. Acceptable fits are obtained only with a combination of $\lambda = 0$ and $\lambda = 1$. (W.W. Jacobs and G.W. Phillips)

5. C.E. Steerman and F.C. Young, Phys. Letters (to be published).

2.3 Small Angle $\lambda$-Dependence in the $^{28}\text{Si}(a,t)^{31}\text{P}$ Reaction

The study of the $^{28}\text{Si}(a,t)^{31}\text{P}$ reaction reported last year was continued. Data were taken in the angular region from 2° to 8° using the experimental arrangement described in that report. The experimental results have already been published.2
This report concerns an attempt to fit the observed small angle differences between the angular distributions for the \( l = 2 \) transitions to the \( j = 3/2 \) and \( j = 5/2 \) states of \(^{31}\text{P}\) using a DWBA code\(^3\) which includes spin-orbit interactions in the form

\[
U_{SO}(r) = V_{SO} \left( \hat{\sigma} \cdot \hat{\lambda} \right) \left( \frac{2}{m^2_c} \right) \frac{1}{r} \frac{d}{dr} f(r),
\]

where \( \hat{\sigma} \) is twice the spin operator, \( \hat{\lambda} \) is the orbital angular momentum of the particle, \( m_\pi \) is the mass of a pion, and \( f(r) \) is the Woods-Saxon shape of the real optical model well.

Optical model parameters were obtained for the entrance channel from an analysis of the elastic scattering of 42-MeV alpha particles from \(^{28}\text{Si}\).\(^4\) We first obtained the triton parameters from a spin-independent optical model analysis\(^5\) of the elastic scattering of 28-MeV \(^3\text{He}\) particles from \(^{28}\text{Si}\).\(^6\)

The strength of the spin-orbit potential in the DWBA code was varied arbitrarily to see if agreement could be found between the theory and the experimental data. The results of these calculations are shown in Fig. 2.3-1, along with the experimental data. The optical model parameters are those of Set 1, given in Table 2.3-1. The strength of the spin-orbit potential has to be quite large (\( V_{SO} = 30 \) MeV) before any substantial change occurs in the predicted angular distributions at small angles. With such large values, however, the rest of the predicted angular distributions are unlike the experimental data.

The predicted angular distributions for the triton elastic scattering had also changed significantly with the inclusion of a large spin-orbit term. Therefore, new triton parameters were obtained by re-analyzing the \(^3\text{He}\) elastic scattering data\(^6\) using a spin-dependent optical model code.\(^7\) Two sets of starting

Fig. 2.3-1. Angular distributions for the \(^{30}\text{Si}(\alpha,t)\) reaction leading to the 1.27-MeV(3/2\(^+\)) and 2.23-MeV(5/2\(^+\)) states of \(^{31}\text{P}\). The curves are the results of the spin dependent DWBA calculations using the optical model parameters of Set 1 (listed in Table 2.3-1) with various spin-orbit potentials.
Table 2.3-1. The optical model parameters used in the analysis of the $^{30}$Si($\alpha$,t)$^{3}$P reaction. The triton parameters were obtained from optical model analyses of the 28-MeV $^{28}$Si($^3$He,$^3$He) elastic scattering data of Ref. 6. The optical model potential was taken to be of the form

$$U_{DP} = -V f(x) - (W + W D \frac{d}{dx} f(x')) - V S (\sigma \cdot \vec{T})(\frac{h}{m c})^2 \frac{1}{r} \frac{d}{dr} f(x) + V_C$$

where $f(x) = [1 + \exp x]^{-1}$

$f(x') = [1 + \exp x']^{-1}$

with $x = (r - r_0 A^{1/3})/a$

$x' = (r - r_I A^{1/3})/a_I$

$V_C$ = Coulomb potential for uniformly charged sphere of radius $R_C = r_C A^{1/3}$.

<table>
<thead>
<tr>
<th></th>
<th>V</th>
<th>W</th>
<th>W_D</th>
<th>V_SO</th>
<th>r_0</th>
<th>r_I</th>
<th>a</th>
<th>a_I</th>
<th>r_C</th>
</tr>
</thead>
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<tr>
<td>$^{28}$Si($\alpha$,t)</td>
<td>197.92</td>
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<td>1.33</td>
<td>1.41</td>
<td>0.618</td>
<td>0.609</td>
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<tr>
<td>$^{3}$P(t,t)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Set 1a</td>
<td>125.67</td>
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<td>125.97</td>
<td>20.9</td>
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<td>1.23</td>
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<td>0.756</td>
<td>0.756</td>
<td>1.23</td>
<td></td>
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<tr>
<td>Set 2</td>
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<td>0.941</td>
<td>1.65</td>
<td>0.823</td>
<td>0.834</td>
<td>1.07</td>
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</tr>
<tr>
<td>Set 3</td>
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<td>33.75</td>
<td>2.5</td>
<td>32.5</td>
<td>1.156</td>
<td>0.933</td>
<td>0.709</td>
<td>0.956</td>
<td>1.07</td>
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<td>0.65</td>
<td>0.65</td>
<td>1.25</td>
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<td></td>
</tr>
</tbody>
</table>

* Used only with calculations which included spin orbit in the triton channel.

parameters were used. The first corresponded to a set of $^3$He parameters used by several authors. The second set was about the same as the parameters in this report. The parameters obtained from these analyses are listed in Table 2.3-1 and are labeled Sets 2 and 3, respectively. The results of the DWBA calculations using these parameters are compared with the experimental data in Figure 2.3-2.

It is seen that for the optical model parameters labeled Set 2 there is
no significant j-dependence predicted at small angles. This effect probably occurs because the imaginary potential's radius is enough larger than the real potential's to prevent the $^3$He particles from feeling the spin orbit force. There is some small angle j-dependence predicted using the optical model parameters of Set 3 but the predicted angular distribution for the transition to the $3/2^+$ state bears little resemblance to the data.

In conclusion, we have not been able to reproduce the observed small angle differences between the angular distributions for the $^{30}$Si ($\alpha$,t) reaction leading to the $3/2^+$ and $5/2^+$ states of $^{31}$P without at the same time destroying any semblance of a fit to the rest of the data. Also, in order to see any significant effect in the predicted angular distributions at small angles, the spin-orbit potential had to be roughly ten times that needed to fit the $^{12}$C($^3$He,$^4$He') spin flip data, and much larger than that needed to fit the $^{12}$C($^3$He,$^3$He) polarization data (a factor of 10 or 40 depending on the system of units used in Ref. 10). The spin orbit potential obtained from the $^3$He polarization measurement is consistent with a theoretical estimate by Kunz et al. Therefore, it is suggested that the effect observed at small angles in the $^{30}$Si($\alpha$,t)$^{31}$P reaction is not primarily due to spin-orbit effects. (W.J. Braithwaite, P.F. Mizera, D.C. Shreve and D.W. Storm)

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3. The authors wish to thank Dr. P.D. Kunz of the University of Colorado for the use of the DWBA code DMUCK.
5. The optical model code FOP written by B. Fernandez was used in the early analysis of the $^3$He elastic scattering.
7. The spin-dependent optical model code was written by W.J. Braithwaite.
9. Section 4.2 of this report (3He Spin-Orbit Strength).

### 2.4 A Measurement of the $^{35}$Cl(p,n)$^{35}$Ar Threshold and Its Relevance to The Vector Coupling Constant

The Conserved Vector Current Theory predicts that all nuclear beta decays should have the same vector coupling constant. Freeman et al. have made a series of measurements on allowed Fermi transitions between $0^+T = 1$ nuclei, where the vector coupling constant is particularly easy to extract, and have found an anomalously high value of the constant in the $^{25}$Mg decay. In this decay the vector coupling constant is six standard deviations above the average of other $0^+ \rightarrow 0^+$ transitions.

It is of particular interest, therefore, to determine whether this type of anomaly can be found in other transitions, particularly in cases where both Fermi and Gamow-Teller transitions contribute. Unfortunately, such a determination is complicated by the requirement that the weak interaction coupling constants and matrix elements of the transition be known to good accuracy. This requirement essentially eliminates most of the candidates for such a study.

Recently, however, Calaprice has done an atomic beam experiment on the $^{35}$Ar($^3p$)$^{35}$Cl mirror transition, in which he measured the Gamow-Teller/Fermi mixing ratio $G_A/\langle f \rangle = g$ to good accuracy and obtained a value of $g = -0.12 \pm 0.03$. With this ratio and an accurate $f$-value of the transition, a determination of the vector coupling constant $G_V$ can be obtained from the relation:

$$G_V^2 = K \langle f \rangle^2 \left(1 + \rho^2\right) \left(\frac{1}{t}\right)^{-1}$$

where $K = (12.3016 \pm 0.0029) \times 10^{-38}$ (erg-cm$^2$sec)$^2$, $\langle f \rangle$ is the Fermi matrix element which is unity for mirror transitions between levels of good isospin. $\rho$ is the mixing ratio mentioned above, and $t$ is the usual $f$-value of the decay, the product of the momentum phase space volume of the decay and its partial half life.

We have therefore undertaken an accurate determination of the $^{35}$Cl(p,n)$^{35}$Ar threshold energy, which is the most uncertain datum in the calculation of $f$. It should also be noted that the present $^{39}$Ar($^3p$)$^{35}$Cl branching
ratio uncertainty also leads to considerable error in the ft-value.

The proton beam of the University of Washington FN tandem accelerator was chopped into 4 μsec pulses with a repetition rate of 12 μsec. Positrons from activity induced by the (p,n) reaction were detected in a plastic scintillator. On either side of the plastic scintillator was located an NaI(Tl) crystal which detected the 0.511 MeV quanta produced when the positrons came to rest and annihilated. These detectors were shielded by lead bricks about 2.5 cm thick, and positrons from the target were only allowed to strike the plastic scintillator by passing through a 0.55 cm diameter hole in the lead shielding.

A fast coincidence between the two annihilation quanta was determined by using a time-to-pulse-height converter which was gated on only when the beam was off the target. The energy signals from the two gamma counters were sent through double-delay-line shaping amplifiers to pulse-height discriminators set

\begin{center}
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figs}
\caption{a, b, and d are excitation functions over the respective (p,n) reaction thresholds. Open circles are total experimental counts and refer to the left scales. Filled circles are counts minus background raised to the 2/3 power and refer to the right scales. c is a (p,p) excitation function over the resonance at 14.233 ± 0.008 MeV proton laboratory energy.}
\end{figure}
\end{center}
to accept only the photopeak of the annihilation radiation. The positron counter was similarly amplified and sent to a pulse-height discriminator which excluded pulses with energies below about 0.8 MeV. The output of the time-to-pulse-height converter was sent to a pulse-height discriminator set to accept coincidences within +8 nsec of the peak of the time spectrum.

These four discriminator signals and an anti-coincidence signal from the beam pulse were used to form a quadrupole slow coincidence and single anti-coincidence. The signal thereby generated was scaled and used to measure the excitation function across the \((p,n)\) thresholds of interest. A proton monitor counter was also scaled as a consistency check. This method proved to give much lower background than simply counting betas in the plastic scintillator when the beam was off. Three energy reference points were selected, two to bracket the \(^{35}\text{Cl}(p,n)\) threshold of interest and a third at higher energy to establish the linearity of the analyzing magnet. These were the \(^{27}\text{Al}(p,n)\) and \(^{58}\text{Ni}(p,n)\) thresholds and the first \(T = 3/2\) analog resonance excited by bombarding \(^{12}\text{C}\) with protons. The energies used for these calibration points were 5.7990 ± 0.0030 MeV, 9.5152 ± 0.0029 MeV, and 14.233 ± 0.008 MeV, the first being a weighted average of values taken from Ref. 10 and the latter two obtained from the review of Marion.\(^5\) Targets were self-supporting foils of natural aluminum, separated (99.99\%) \(^{58}\text{Ni}\), and natural carbon, with thicknesses of 0.74, 0.34 and 0.020 mg/cm\(^2\), respectively. The measured excitation functions for these calibrations are shown in Fig. 2.4-1.

For the measurement of the \(^{35}\text{Cl}(p,n)\) threshold a target of Saranwrap (polyyvinyl chloride, about 50\% chlorine by weight) with a thickness of 2.2 mg/cm\(^2\) was used. The relative heights of the carbon and chlorine elastic scattering peaks were monitored during the course of the excitation function to make sure there was no time-dependent loss of chlorine due to beam cracking. Figure 2.4-1c shows the excitation function, which with the calibrations measured during the same run, implies that the threshold energy is 6.9689 ± 0.0035 MeV.

Table 2.4-1 shows a comparison with previous measurements. The principal source of uncertainty in this measurement lies in the energy uncertainties of the calibration points. Figure 2.4-2 shows the magnet constant \(k\) derived from each of the energy calibration points. These three determinations are in good

<table>
<thead>
<tr>
<th>(\text{Energy (MeV)})</th>
<th>(\text{Reference})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9685 ± 0.0035</td>
<td>(^{35}\text{Cl}(p,n)) threshold</td>
</tr>
<tr>
<td>4.96 ± 0.04</td>
<td>(^{35}\text{Ar}(\beta^+)) spectrum</td>
</tr>
<tr>
<td>4.93 ± 0.05</td>
<td>(^{35}\text{Ar}(\beta^+)) spectrum</td>
</tr>
<tr>
<td>4.944 ± 0.02</td>
<td>(^{35}\text{Cl}(p,n)) threshold</td>
</tr>
<tr>
<td>5.13 ± 0.04</td>
<td>(^{32}\text{S}(\alpha,n)) threshold</td>
</tr>
</tbody>
</table>

Table 2.4-1. Comparison of End-Point Energy Determinations for The \(^{35}\text{Ar}(\beta^+)^{35}\text{Cl}\) Beta Decay.

Present work
- Kistner & Rustad\(^7\)
- Wallace & Welch\(^8\)
- Nelson et al.\(^11\)
- Nelson et al.\(^11\)
agreement, and indicate no non-linearities in the analyzing magnet over the energy range studied.

From the threshold energy determination described above, the positron end-point energy $E_{\text{max}}$ was determined to be $4.9685 \pm 0.0035$ MeV, in agreement with previous measurements of lower accuracy as seen in Table 2.4-1. The phase-space volume $f$ may then be calculated from the end-point energy by the relation:

$$f = \frac{1}{m^7 c^7} \int_0^{p_{\text{max}}} F(Z, p)^2 q^2 dp$$

where $F$ is the Fermi function and $p$ and $q$ are the electron and neutrino momenta. This gives $f = 3148 \pm 10$.

The partial half-life $t$ is just the half-life of the $^{35}$Ar decay divided by the ground state branching ratio. Previous measurements give an average value for the half-life$^{6-9}$ of $1.804 \pm 0.012$ sec and a value for the ground state branching ratio$^9$ of $93 \pm 2.3\%$. These, together with corrections as calculated by Calaprice,$^3$ lead to a corrected $t$-value of $5762 \pm 174$ which when combined with the transition mixing ratio obtained by Calaprice$^3$ gives a value for the vector coupling constant of $G_V = (1.392 \pm 0.020) \times 10^{-49}$ erg·cm$^3$. Although this value within errors indicated is consistent with the average $G_V$ of $(1.4034 \pm 0.0016) \times 10^{-49}$ erg·cm$^3$ determined by Freeman et al.$^2$ for pure Fermi transitions, it is nevertheless considerably lower. A more accurate comparison between these values would be of interest.

The major contribution to $G_V$ error for the $^{35}$Ar($^+^\beta^+$)$^{35}$Cl transition arises from uncertainty in the branching ratio. It is therefore most important that this quantity be remeasured with higher precision. (J.G. Cramer and N.F. Mangelson)

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A Study of (d,p) Stripping on $^{72}$Ge at 11 MeV

This study has been undertaken to obtain information about the levels of $^{73}$Ge by bombarding $^{72}$Ge with 11 MeV deuterons. $^{73}$Ge is interesting because it consists of a semi-closed shell of 32 protons, a closed shell of 40 neutrons plus an additional neutron. This single neutron should allow one to investigate the neutron bound state wave function involved in a DWBA calculation such as the program DWUCK.\(^1\) The incoming ($^{72}$Ge (d elastic)) and outgoing ($^{73}$Ge (p elastic)) optical model potentials can be found by an analysis of the elastic angular distributions.

The present work is related to a study done last year on (d,p) stripping on $^{90}$Zr near the Coulomb barrier.\(^2\) Now, however, we are quite a bit above the Coulomb barrier for Ge (6 MeV) so that the features of the angular distributions, which will allow the extraction of L and possibly J values for the energy levels, will be more distinct.

Angular distributions have been taken from about 20° to 130° and up to 3 MeV in excitation energy. Since there are more than 20 energy levels in this region it was necessary to write a special data analysis computer program. This program utilized the special CRT display and light pen peripheral equipment of our SDS 930 computer system.

It was found that target nonuniformities have made some of the data unreliable but the experiment will be repeated in the near future with new targets. Other proposals for the future include comparison of results with those obtainable from an experiment on $^{72}$Ge which has a neutron-hole configuration as well as comparison with other similar closed shell systems such as $^{90}$Zr. (J.G. Cramer, R.A. Hinrichs and D.L. Oberg)

1. P.D. Kunz, Program DWUCK (University of Colorado).
A Study of Charge Exchange Effects in Zr(d,p) Reactions

Angular distributions and excitation functions have been taken to study charge exchange effects in several Zr isotopes. $^{90}$Zr(d,p)$^{91}$Zr excitation functions were taken over the energy range 5 to 11 MeV. Figure 2.6-1 shows the measured differential cross sections in 200 keV steps at 50° and 170°, along with the angular integrated cross section between 35° and 150°. A dip is seen in the excitation function at 170° for the transition to the d$_{5/2}$ state at 7.05 MeV and also to the s$_{1/2}$ state at 8.26 MeV. These anomalies have been previously observed$^4$ in the excitation function at backward angles and are found to lie at energies corresponding to the opening of the analog ground state and first excited state in $^{91}$Nb by the (d,n) reaction. This anomaly has been attributed to a charge exchange process in which there is a strong coupling between the (d,n) and analogous (d,p) channels.$^2$ The source of the anomaly has been suggested to be due to the rapid energy dependence of the outgoing p$_{3/2}$ neutron partial wave. The arrows in Fig. 2.6-1 denote the thresholds for the reactions $^{90}$Zr(d,n)$^{91}$Nb(d$_{5/2}$), $^{90}$Zr(d,n)$^{91}$Nb(s$_{1/2}$), and $^{90}$Zr(d,n)$^{91}$Nb(d$_{3/2}$). However, DWBA calculations made with the code TSALLY also show a dip in the s$_{1/2}$ channel at this energy. Thus the existence of a charge exchange effect at this energy would be masked by this minimum. No anomaly is seen in the d$_{3/2}$ excitation function at 170°. This has been attributed to the fact that the threshold energy of 9.11 MeV is farther above the Coulomb barrier, allowing a larger number of partial waves to contribute and so mask the effect of the anomaly in the p$_{3/2}$ neutron wave.

Angular distributions have been taken at 7.05 MeV and above and below this anomaly (as described in Sec. 2.9 of this report). Transitions to the ground state and several excited states at 7.05 MeV for $^{91}$Zr are shown in Fig. 2.6-2, along with DWBA calculations. The experimental cross sections show a pronounced dip at forward angles, which is not matched by the DWBA calculations with any of the sets of optical model parameters considered in Sec. 2.9. This anomaly occurs in transitions to the d$_{5/2}$ and d$_{3/2}$ states but not in the higher excited states.

If the spectroscopic factors are extracted at these forward angles (as is usually done) by the normalization of the experimental and calculated angular distributions, a dip is found in S at this energy for these two states (Fig. 2.6-3). (This anomalous behavior was also observed by Lynen et al.$^3$ in the d$_{5/2}$, s$_{1/2}$ and d$_{3/2}$ channels; it was implied from this a coupling of the (d,n) channel not only to the ground state of the (d,p) transition but also to transitions to its excited states.) However, as seen in Fig. 2.6-1, no dip is seen.

Fig. 2.6-1. $^{90}$Zr(d,p)$^{91}$Zr excitation function to the d$_{5/2}$, s$_{1/2}$ and d$_{3/2}$ states; Angular integrated cross-section for the same states.
in the angular integrated cross sections at 7.05 MeV.

To simulate the effect of an apparent increased absorption of higher partial wave protons at this energy (corresponding to a coupling with the emission of low energy neutrons in the \((d,n)\) channel) an \(l\)-dependent potential was included in the proton imaginary potential by using the DWBA code DWUCK. However, the observed dip at forward angles has not been able to be produced by this method. A discontinuous change in the appropriate proton optical model parameters at this energy is another possibility, as the relative importance of the various partial waves may not be the same for stripping as for elastic scattering. The inclusion of a charge exchange term in the proton optical potential (which has proved successful for the prediction of the anomaly in the excitation function for the \(^{90}\text{Zr}(d,p)\) \(^{91}\text{Zr}(d_{5/2})\) reaction) might apply to the \(d_{5/2}\) case but does not include coupling to non-analogous channels, and so it is not applicable to the \(d_{3/2}\) state.

**Fig. 2.6-3.** Spectroscopic factor of \(^{90}\text{Zr}(d,p)\) \(^{91}\text{Zr}\) to the \(d_{5/2}\) and \(d_{3/2}\) states, as a function of energy.

**Fig. 2.6-2.** \(^{90}\text{Zr}(d,p)\) \(^{91}\text{Zr}\) angular distributions at 7.05 MeV to the ground and excited states in \(^{91}\text{Zr}\). DWBA calculations are made with the code TSALLY.

A similar investigation is being carried out in \(^{92}\text{Zr}\) and \(^{94}\text{Zr}\) at energies on or near the observed \((d,p)\) anomaly in these isotopes. Some of these results are shown in Fig. 2.6-4. The \(^{92}\text{Zr}\) angular distribution also has a dip at forward angles in the \(d_{3/2}\) channel at 7.4 MeV (although there is none at 11 MeV). No such effect is seen in the \(^{94}\text{Zr}(d,p)\) angular distribution at its \((d,n)\) threshold to the analog state (7.6 MeV). The same set of optical model parameters was used in all cases.

In conclusion it appears difficult in the case of the \(Zr(d,p)\) anomalies to say that the anomaly in the value of \(S\) is due to anything more than a dependence of the DWBA upon
elastic scattering parameters. A further study of the angular distributions in this area is underway. (J.G. Cramer, R.A. Hinrichs, D.L. Oberg and G.W. Phillips)

4. F.D. Kunz, DWBA code DWUCK, University of Colorado (1967).

Fig. 2.6-4. \(^{92}\text{Zr}(d,p)^{92}\text{Zr}, E=74\text{ MeV}\) and \(^{94}\text{Zr}(d,p)^{95}\text{Zr}, E=76\text{ MeV}\) angular distributions to the \(d_{5/2}\) and \(d_{3/2}\) states. The DWBA calculations use the same parameters.

2.7 Charge Exchange Effects in the (d,p) Reaction Leading to States in \(^{93,95}\text{Zr}, \(^{93,95}\text{Mo}\) and \(^{141}\text{Ce}\)

Anomalous behavior in the 170° excitation functions for the \(^{90}\text{Zr}(d,p)^{91}\text{Zr}\) \((d_{5/2}, g.s.)\) and \(^{90}\text{Zr}(d,p)^{91}\text{Zr}(s_{1/2}, 1.21\text{ MeV})\) reactions has been observed at energies near the \((d,n)\) threshold to the corresponding IAS.\(^1\) It was suggested that this phenomenon could be accounted for by a charge-exchange process which would couple analogous outgoing channels, i.e., the \((d,p)\) channel to the parent state and the \((d,n)\) channel to the IAS. Distorted wave calculations, which explicitly include a charge-exchange term in the proton optical potential,\(^2\) have been carried out by Tamura and Watson.\(^3\) Their results essentially reproduce the observed anomaly in the \(^{90}\text{Zr}(d,p)^{91}\text{Zr}(d_{5/2}, g.s.)\) cross section. They contend that the whole source of the anomaly is the strong energy dependence of the outgoing \(d_{3/2}\) neutron partial wave in the exchange amplitude.

The effect attributed to charge exchange in the proton channel has been observed in very few nuclei and for only one or two levels in each particular nucleus.\(^1,4,5\) Thus this process appears to be somewhat selective and it is therefore of interest to see whether the effect persists through the Zr and Mo isotopes. Related to this, \(^{140}\text{Ce}\) was studied since it is near a mass region where the s-wave neutron strength function is a maximum. Furthermore, a complete understanding of the charge-exchange process must necessarily explain both the \((d,n)\) and \((d,p)\) cross sections. The \((d,n)\) reaction to the relevant IAS has
been studied previously in several Mo and Zr isotopes, and the present (d,p) study complements this work.

The (d,p) excitation functions were taken between 5.0 MeV and 9.7 MeV for the Mo and Zr isotopes, and between 10.0 MeV and 13.4 MeV for \(^{140}\)Ce. Si(Li)-drifted) detectors were placed at laboratory angles of 165°, 145° and 90°. Self-supporting foils of natural Ce and enriched \(^{92,94}\)Mo and \(^{92,94}\)Zr were used as targets.

The 165° data (Fig. 2.7-1) and the 145° data (not shown) for the transitions to the ground state (d5/2) of \(^{93,95}\)Zr and \(^{93,95}\)Mo show anomalous behavior at the energy near the (d,n) threshold to the corresponding IAS. This behavior cannot be reproduced by standard DWBA calculations. At 165°, the effect in \(^{93}\)Zr and \(^{95}\)Zr is comparable to that observed by Moore et al., in the study of \(^{91}\)Zr; in \(^{95}\)Mo and \(^{93}\)Mo the effect is less prominent. For all these isotopes, the anomaly at 145° is smaller in magnitude than at 165°. At 90° (not shown) the anomaly is further reduced in magnitude and is seen only in the Zr data.

The excitation functions for the transitions to the first s1/2 state of \(^{93,95}\)Zr and \(^{93,95}\)Mo (Fig. 2.7-2) exhibit a broad minimum in the energy region near the (d,n) threshold to the IAS in the case of \(^{95}\)Mo the curve is for an unresolved doublet (1/2^+,3/2^+). In particular, one sees that these large minima occur at about the same incident laboratory energy in the Zr isotopes, including the \(^{91}\)Zr data of Moore et al. However, standard DWBA calculations for the 165° excitation function in this mass and energy region also show a minimum. Since these large DWBA minima may mask any charge-exchange effects, the observed broad minima in the s1/2 excitation functions of the Zr and Mo isotopes may only be partly attributable to coupling effects. Nevertheless, there is evidence that an anomaly is present at about 8.7 MeV in the \(^{95}\)Zr (s1/2) excitation function.

Fig. 2.7-1. The energy dependence for each reaction shown above exhibits a cusp at the (d,n) threshold to the corresponding IAS. In the case of \(^{141}\)Ce (g.s.,f7/2) the effect can be reproduced by standard DWBA calculations, whereas the effects in Zr and Mo are believed to be due to the charge-exchange coupling. The arrows indicate the threshold energy for the (d,n) channel. The Ce data is normalized to the data of Holm and Martin (Ref. 9). The solid curve through the data points merely indicates the general trend.
The $^{92}\text{Zr}(d,p)^{93}\text{Zr}$ ($s_{1/2}$, 0.96 MeV) excitation function at 165° shows a small peak (≈7% in magnitude and ≈40 keV in width) at a deuteron energy of 7.38 MeV (see insert in Fig. 2.7-2). This energy corresponds to the (d,n) threshold of the $d_{5/2}$(g.s.)-IAS in $^{93}\text{Nb}$. The charge exchange process described above couples only analogous channels and therefore cannot account for this small observed effect. In this energy region the deuteron elastic scattering excitation function at 165° is smooth.

No evidence for anomalous behavior was found in the (d,p) cross section to the first $d_{3/2}$ parent analog states in $^{93,95}\text{Zr}$ or $^{93,95}\text{Mo}$ and the $1/2^+$ (1.06 MeV) state in $^{95}\text{Mo}$.

The 165° excitation functions for the reaction leading to the ground ($f_{7/2}$) and first excited ($p_{3/2}$) states of $^{141}\text{Ce}$ are also shown in Figs. 2.7-1 and 2.7-2, respectively. Although these curves show a break in the cross section at the relevant (d,n) threshold energy, the break may not be due to a charge-exchange process since standard DWBA calculations reproduce this behavior at the proper energy.

In conclusion, the (d,p) anomaly definitely does persist in the reaction leading to the $d_{5/2}$ ground state in $^{93,95}\text{Zr}$ and $^{93,95}\text{Mo}$. The effect is apparently diminished in magnitude both at succeeding forward angles for a particular reaction channel and with increasing (d,n) threshold energy to the IAS in a given nucleus. Finally, since standard DWBA calculations show that the anomaly can be masked, care must be taken in its identification. (N. Cue, R. Heffner, C. Ling and P. Richard)


2.8 Re-analysis of the (d, 3He) Studies on 90Zr, 89Y and 88Sr and the
Possible Configuration Mixing in the Ground States of 88Sr and 90Zr

The (d, 3He) studies on 90Zr, 89Y and 88Sr reported earlier\(^1\) have been
re-analyzed. This re-analysis was
prompted by the following considerations: 1) A DWBA code which included
spin-orbit interactions and a correc-
tion for finite range became avail-
able.\(^2\) 2) Consistent sets of \(^3\)He opti-
cal model parameters have been
presented recently in the literature.\(^3-5\)
3) Optical model parameters for the
elastic scattering of deuterons from
90Zr have been obtained.\(^7,8\)

There had been several uncer-
tainties in the results of the pre-
vious DWBA analysis\(^6\) of these reac-
tions. Uncertainties arose from the
use of a lower cut-off on the radial
integral which introduced an uncer-
tainty of about \(\pm30\%\) in the spectro-
scopic factors for the \(l = 3\) and
\(l = 4\) transitions. Also, the use of
an approximate prescription\(^9,10\) for
including the effects of spin-orbit
effects introduced fairly large un-
certainties. It was hoped that an
analysis which used more consistent
optical model parameters and a DWBA
code which included the effects of
spin-orbit interactions and a

Fig. 2.8-1. Angular distributions for the \(^{90}\)Zr(d, \(^3\)He) reaction leading to the
ground state, 1.51- and 1.75-MeV states
of \(^{89}\)Y. The curves are the results of
the spin-dependent DWBA code.
correction for finite range would substantially reduce these uncertainties.

Sample fits to the experimental angular distributions are shown in Fig. 2.8-1 where the differential cross sections for the $^{90}$Zr$(d,^3$He$)$ reaction leading to the ground state ($1/2^-$), 1.51-MeV ($3/2^-$), and 1.75-MeV ($5/2^-$) states of $^{89}$Y are compared with the spin-dependent theory. The optical model parameters used in this analysis are listed in Table 2.8-1. The finite range parameter was taken to be that calculated by Bassel.\textsuperscript{11} It should be noted that no radial cut-off was required in this analysis.

Table 2.8-1. Optical model parameters used in the spin-dependent DWBA analysis of the $(d,^3$He$)$ reaction on $^{90}$Zr, $^{89}$Y and $^{88}$Sr.

The optical potential is of the form

$$U(r) = -V(1 + \exp (x))^{-1} - \text{i}[\frac{d}{dx'}][1 + \exp (x')]^{-1} - V_{SO} \left( \frac{x}{r} \right) \left( \frac{\sigma}{r} \right) \frac{1}{r} \left[ 1 + \exp x \right]^{-1} + V_{\text{Coulomb}}$$

where $x = (r - R)/a$, $x' = (r - R')/a'$, $R = r_0^A A^{1/3}$, $R' = r_1^A A^{1/3}$, and the Coulomb potential $V_{\text{C}}$ is taken as that arising from a uniformly charged sphere of radius $R_0 = r_c^A A^{1/3}$.

<table>
<thead>
<tr>
<th></th>
<th>$V$</th>
<th>$W$</th>
<th>$W'$</th>
<th>$V_{SO}$</th>
<th>$R_0$</th>
<th>$R_1$</th>
<th>$a$</th>
<th>$a'$</th>
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<td>52.56</td>
<td>3.26</td>
<td>1.099</td>
<td>1.344</td>
<td>0.835</td>
<td>0.747</td>
<td>1.3</td>
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<td>$^3$He</td>
<td>175.0</td>
<td>22.0</td>
<td>0</td>
<td>8</td>
<td>1.14</td>
<td>1.60</td>
<td>0.723</td>
<td>0.81</td>
<td>1.40</td>
</tr>
<tr>
<td>Bound State</td>
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<td>8</td>
<td>1.25</td>
<td>0.65</td>
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<td></td>
<td></td>
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<td></td>
</tr>
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</table>

(a) Taken from Reference 7.
(b) Taken from Reference 3.

The spectroscopic factors were obtained from the expression

$$\frac{d\sigma}{d\Omega_{\text{exp}}} = \frac{2S_b + 1}{2S_a + 1} \cdot N \cdot \sum_{l,j} \frac{\sigma_{l,j}(\theta)}{2l + 1}$$

where $S_b$ and $S_a$ are the spins of the $^3$He and deuteron, respectively, $N$ is the normalization constant,\textsuperscript{11} $S_{l,j}$ is the spectroscopic factor, $\ell$ and $j$ are the orbital and total angular momentum allowed by the selection rules, and
$\sigma_{ij}$ is the output of the spin-dependent DWBA code. The constant $N$ was obtained by assuming that the spectroscopic factor for the $^{89}$Y($d$,$^3$He) reaction leading to the ground state of $^{88}$Sr is unity. This assumption results in a value of $N = 4.84$ which is slightly larger than the theoretical value of 4.42 obtained by Bassel.\textsuperscript{11}

As in the analysis of Ref. 1, the individual spectroscopic factors for the mixed $l = 1,3$ transitions to the $2^+$ states of $^{88}$Sr could not be extracted with any degree of accuracy. The sums of the spectroscopic factors ($S_1 + S_3$) for these mixed transitions were extracted in the same way as in Ref. 1 and are relatively insensitive to the ratio $S_1/S_3$.

All the spectroscopic factors extracted from the present analysis are compared with those extracted from the previous analysis\textsuperscript{1} in Table 2.8-2. The model spectroscopic factors of Table 2.8-2 were obtained by making the same assumptions about the wave functions as were made in Ref. 1. These

Table 2.8-2. Spectroscopic factors for ($d$,$^3$He) reaction on $^{90}$Zr, $^{89}$Y and $^{88}$Sr. Columns 1, 2 and 3 list the reaction, final state excitation energy and spin and parity. Column 4 lists the spectroscopic factors obtained by the spin-independent DWBA analysis of Ref. 1. Column 5 lists the spectroscopic factors obtained in this analysis and Column 6 lists the model spectroscopic factors.

<table>
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<tr>
<th>Reaction</th>
<th>Final State</th>
<th>$J^+$</th>
<th>$S^{(1)}$</th>
<th>$S^{(2)}$</th>
<th>$S$ Model</th>
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<td>$^{90}$Zr($d$,$^3$He)</td>
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<td>1.14</td>
<td>1.03</td>
<td>$2A_2^a$</td>
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<tr>
<td></td>
<td>0.906</td>
<td>9/2\textsuperscript{+}</td>
<td>0.51</td>
<td>0.83</td>
<td>$2B_2^a$</td>
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<tr>
<td></td>
<td>1.75</td>
<td>5/2\textsuperscript{−}</td>
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<td>3.4</td>
<td>6</td>
</tr>
<tr>
<td>$^{89}$Y($d$,$^3$He)</td>
<td>g.s.</td>
<td>0\textsuperscript{+}</td>
<td>1.0</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.24</td>
<td>2\textsuperscript{+}</td>
<td>2.2</td>
<td>2.6\textsuperscript{b}</td>
<td>2.5</td>
</tr>
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<td>2\textsuperscript{+}</td>
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<td>2.9\textsuperscript{b}</td>
<td>2.5</td>
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<td>3.48</td>
<td>(1\textsuperscript{+})</td>
<td>1.2</td>
<td>1.9</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3.64</td>
<td>(3\textsuperscript{+})</td>
<td>2.2</td>
<td>4.3</td>
<td>3.5</td>
</tr>
<tr>
<td>$^{88}$Sr($d$,$^3$He)</td>
<td>g.s.</td>
<td>3/2\textsuperscript{−}</td>
<td>2.6</td>
<td>2.6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>(5/2)\textsuperscript{−}</td>
<td>2.2</td>
<td>3.3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>0.84</td>
<td></td>
<td></td>
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<td>0</td>
</tr>
</tbody>
</table>

a. $A$ and $B$ are defined in the text.
b. These numbers correspond to $S_1 + S_3$ and have an uncertainty of ±25%.
assumptions are:

a) The neutron configurations of all the states considered are the same.
b) The ground state of $^{88}\text{Sr}$ corresponds to the proton configuration $(p_3/2)^6(f_5/2)^8$.
c) The excited states of $^{88}\text{Sr}$ studied in the present experiment correspond to the proton particle-hole configurations $(p_{1/2})(p_{3/2})^{-1}$ and $(p_{1/2})(f_{5/2})^{-1}$.
d) The ground state of $^{90}\text{Zr}$ corresponds to the configuration $A(p_{1/2})^2 + B(g_9/2)^2$.
e) The 1.51- and 1.75-MeV states of $^{89}\text{Y}$ correspond to proton hole configurations with the same $(p_{1/2})^2 - (g_9/2)^2$ mixing as the ground state of $^{90}\text{Zr}$.
f) All the other states studied are either single-particle or single-hole states.

It is seen in Table 2.8-2 that there are fairly large discrepancies between the spectroscopic factors obtained from the different DWBA analyses. Most of these discrepancies can be attributed to the uncertainties introduced in the previous analysis either by the lower cut-off on the radial integral or by the prescription for the inclusion of spin-orbit effects. (The precession for mocking up the effect of the spin-dependence introduced a 20% difference between the predicted magnitudes of the angular distributions for $p_{1/2}$ and $p_{3/2}$ transitions, while the spin-dependent DWBA analysis predicted no more than a 3% difference for these transitions.) These discrepancies should be considered as failings of the earlier analysis.

In comparing the experimental and the model spectroscopic factors of Table 2.8-2 we find that the spectroscopic factors extracted from the present analysis for the transitions to the excited states of $^{88}\text{Sr}$ are all larger than those predicted by the model. This discrepancy could either be due to a failing of the DWBA theory or to an incorrect assumption in obtaining the normalization constant $N$. The assumptions made in obtaining $N$ are that the ground state of $^{88}\text{Sr}$ is closed and that the ground state of $^{89}\text{Y}$ is a $p_{1/2}$ proton plus the $^{88}\text{Sr}$ core.

Evidence that the model wave function for the ground state of $^{88}\text{Sr}$ may be incorrect has been presented by Bassani et al.\textsuperscript{12} who have studied the $^{88}\text{Sr}(^3\text{He},d)$ reaction leading to the 1.51-MeV (3/2\textsuperscript{+}) state of $^{89}\text{Y}$. If this transitions proceeds by a simple

Fig. 2.8-2. The angular distribution for the $^{88}\text{Sr}(d,^3\text{He})$ reaction leading to the 0.84-MeV state of $^{87}\text{Rb}$. The curves are the results of the spin-dependent DWBA for $\ell = 1, j = 1/2$ and $\ell = 1, j = 3/2$ transitions.
stripping mechanism, then the \( ^{3}P_{3/2} \) orbital of the ground state of \(^{88}\text{Sr}\) must not be closed in protons. Further, although much weaker, evidence that the ground state of \(^{88}\text{Sr}\) is mixed is provided by the \(^{88}\text{Sr}(d,^{3}\text{He})\) reaction to the 0.84-MeV state of \(^{87}\text{Rb}\). The spin and parity of this state are not known. The angular distribution for the transition to this state is compared with \( l = 1, \ j = 1/2 \)
and \( j = 3/2 \) spin-dependent DWBA predictions in Fig. 2.8-2. Although the experimental errors are quite large, the shape of the angular distribution is suggestive of \( j = 1/2 \). This is consistent with simple shell-model calculations which predict a \( ^{3}P_{1/2} \) state at about this energy. If the spin of this state is 1/2, then the transition can proceed by a simple pick-up mechanism only if the ground state of \(^{88}\text{Sr}\) contains some \( (^{3}P_{1/2})^{2} \)
configuration.

In view of these findings, (a) spectroscopic factors larger than the model spectroscopic factors for the \((d,^{3}\text{He})\) reaction leading to the excited states of \(^{88}\text{Sr}\), (b) a spectroscopic factor greater than zero for the \(^{88}\text{Sr}(^{3}\text{He},d)\) reaction leading to a predominantly \( ^{3}P_{3/2} \) hole state of \(^{89}\text{Y}\), and (c) what might be a \( ^{3}P_{1/2} \) pick-up from the ground state of \(^{88}\text{Sr}\) it seems reasonable to modify the assumption that the ground state of \(^{88}\text{Sr}\) is closed in protons. If the model wave functions for the ground state of \(^{89}\text{Y}\), the ground state of \(^{88}\text{Sr}\) and the 0.84-MeV state of \(^{87}\text{Rb}\) are assumed to be

\[
\psi(^{89}\text{Y},g.s.) = (^{3}P_{3/2})^4 P_{1/2}
\]

\[
\psi(^{88}\text{Sr},g.s.) = a(^{3}P_{3/2})^4 + b(^{3}P_{3/2})^2 P_{1/2}^2
\]

and

\[
\psi(^{87}\text{Rb},0.84) = (^{3}P_{3/2})^2 P_{1/2}
\]

respectively, then the relative spectroscopic factors for the \((d,^{3}\text{He})\) transitions to the ground state of \(^{88}\text{Sr}\) and the 0.84-MeV state of \(^{87}\text{Rb}\) determine the ratio \( a^2/b^2 \approx 2.5 \pm 0.5 \). The condition that \( a^2 + b^2 = 1 \) implies that

\[
a^2 = 0.72 \pm 0.04
\]

\[
b^2 = 0.28 \pm 0.04
\]

These numbers are in good agreement with the configuration mixing in the ground state of \(^{88}\text{Sr}\) which is implied by the spectroscopic factor reported by Bassani et al. for the \(^{88}\text{Sr}(^{3}\text{He},d)\) transition to the 1.51-MeV state of \(^{89}\text{Y}\). (Their spectroscopic factor implies \( b^2 \approx 0.2 \) if the 1.51-MeV state of \(^{89}\text{Y}\) is assumed to be \( (^{3}P_{3/2})^{-1}(^{1}P_{1/2})^2 \). If there are any other configurations in the wave function of the 1.51-MeV state, then the mixing implied in the ground state of \(^{88}\text{Sr}\) will be increased.)

If the preceding analysis is correct, then all the experimental spectroscopic factors of Table 2.8-2 will be reduced because of the assumption originally made in obtaining \( N \). The experimental and model spectroscopic factors obtained assuming configuration mixing in the ground state of \(^{88}\text{Sr}\) are listed in Table 2.8-3 along with the assumed proton configuration. The experimental
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Final State</th>
<th>J(^\pi)</th>
<th>S</th>
<th>S Model</th>
<th>Model Proton Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{90})Zr(d,(^3)He)</td>
<td>g.s.</td>
<td>1/2(^-)</td>
<td>0.75</td>
<td>2(A^2)</td>
<td>(P_{1/2})</td>
</tr>
<tr>
<td></td>
<td>0.905</td>
<td>9/2(^+)</td>
<td>0.65</td>
<td>2(B^2)</td>
<td>(E_{9/2})</td>
</tr>
<tr>
<td></td>
<td>1.51</td>
<td>3/2(^-)</td>
<td>1.9</td>
<td>2.7 (a)</td>
<td>(P_{3/2}^{-1}(D(P_{1/2})^2 + E(E_{9/2})^2)) (b)</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>5/2(^-)</td>
<td>2.5</td>
<td>4.0 (a)</td>
<td>(F_{5/2}^{-1}(D(P_{1/2})^2 + E(E_{9/2})^2)) (b)</td>
</tr>
<tr>
<td></td>
<td>1.51</td>
<td>3/2(^-)</td>
<td>1.9</td>
<td>1.5 (a)</td>
<td>(P_{3/2}^{-1}(P_{1/2})^2)</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>5/2(^-)</td>
<td>2.5</td>
<td>2.3 (a)</td>
<td>(F_{5/2}^{-1}(P_{1/2})^2)</td>
</tr>
<tr>
<td>(^{89})Y(d,(^3)He)</td>
<td>g.s.</td>
<td>0(^+)</td>
<td>0.72</td>
<td>0.72</td>
<td>0.85((P_{3/2})^4 + 0.53(P_{3/2})^2(P_{1/2})^2)</td>
</tr>
<tr>
<td></td>
<td>1.84</td>
<td>2(^+)</td>
<td>1.9</td>
<td>2.5</td>
<td>(a(P_{3/2}^{-1},P_{1/2})<em>2 + b(f</em>{5/2}^{-1},P_{1/2})_2)</td>
</tr>
<tr>
<td></td>
<td>3.21</td>
<td>2(^+)</td>
<td>2.1</td>
<td>2.5</td>
<td>(a'(P_{3/2}^{-1},P_{1/2})<em>2 + b'(f</em>{5/2}^{-1},P_{1/2})_2)</td>
</tr>
<tr>
<td></td>
<td>3.48</td>
<td>1(^+)</td>
<td>1.4</td>
<td>1.5</td>
<td>((P_{3/2}^{-1},P_{1/2})_1)</td>
</tr>
<tr>
<td></td>
<td>3.64</td>
<td>3(^+)</td>
<td>3.1</td>
<td>3.5</td>
<td>((f_{5/2}^{-1},P_{1/2})_3)</td>
</tr>
<tr>
<td>(^{88})Sr(d,(^3)He)</td>
<td>g.s.</td>
<td>3/2(^-)</td>
<td>1.9</td>
<td>2.9</td>
<td>((P_{3/2})^{-1})</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>5/2(^-)</td>
<td>2.4</td>
<td>4.3</td>
<td>((f_{5/2})^{-1})</td>
</tr>
<tr>
<td></td>
<td>0.84</td>
<td>1/2(^-)</td>
<td>0.6</td>
<td>0.6</td>
<td>((P_{3/2})^{-2} P_{1/2})</td>
</tr>
</tbody>
</table>

a. The ground state of \(^{90}\)Zr is assumed to be

\[
\psi(\(^{90}\)Zr, g.s.) = A(P_{1/2})^2 + B(E_{9/2})^2 + C\psi_{\text{other}}
\]

with the values of A, B and C given in the text.

b. The ratio D/E was assumed equal to A/B.

spectroscopic factors for the transitions to the excited states of \(^{88}\)Sr are now consistent with the model.

If the preceding analysis is correct, then the spectroscopic factors of Table 2.8-3 open some interesting questions. The sum of the spectroscopic
factors for the $^90\text{Zr}(d,^3\text{He})$ transitions to the ground and first excited states of $^{89}\text{Y}$ is substantially smaller than 2. This seems to imply that the model wave functions of the states in question are not correct. If the ground and first excited states of $^{89}\text{Y}$ are assumed to be good single-particle states, as seems reasonable since the extra-core proton will block some of the mixing from the $^{88}\text{Sr}$ core, then the small spectroscopic factors imply that the ground state of $^{90}\text{Zr}$ contains more mixing than has been previously suspected.\textsuperscript{13-21} There have been several experimental measurements\textsuperscript{13,16,17,19} of the mixing in the ground state of $^{90}\text{Zr}$. In three experiments\textsuperscript{13,16,19} the ratio of $(p_{1/2})^2$ to $(g_{9/2})^2$ mixing has been measured. In each case it was assumed that there was no additional mixing. The fourth experiment\textsuperscript{17} was a measurement of the $^{89}\text{Y}(^3\text{He},d)$ reaction leading to the ground (0\textsuperscript{+}) and 1.75-MeV (0\textsuperscript{+}) states of $^{90}\text{Zr}$. This measurement determined the ratio of $(p_{1/2})^2$ configurations in these two 0\textsuperscript{+} states. Again it was assumed that the mixing only occurred between the $(p_{1/2})^2$ and $(g_{9/2})^2$ configurations.

The present analysis suggests that if the ground state of $^{90}\text{Zr}$ is written as

$$\psi^{^{90}\text{Zr},g.s.} = A(p_{1/2})^2 + B(g_{9/2})^2 + C\psi_{\text{other}}$$

where $\psi_{\text{other}}$ is some other configuration, then the coefficients $A$, $B$ and $C$ will be

$$A^2 = 0.37 \pm 0.04$$

$$B^2 = 0.33 \pm 0.05$$

$$C^2 = 0.30 \pm 0.05$$

The work of Freedom \textit{et al.}\textsuperscript{19} also suggests that such mixing occurs. Their argument is based on sum rule strengths leading to the $p_{3/2}$ proton hole states. Also, the results of the $^{89}\text{Y}(^3\text{He},d)$ study\textsuperscript{17} are slightly different than the results of the other experiments. (The value of $A^2$ (assuming $A^2 + B^2 = 1$) of Ref. 17 is 0.73 \pm 0.03 in comparison to values from the other experiments ranging from 0.55 to 0.64.) This is consistent with the present speculation that the ground state of $^{90}\text{Zr}$ has more mixing than normally assumed.

A final word of caution should be added, however. The preceding discussion has been based on the assumption that the probability of two-step processes is negligible. If two-step processes are not too improbable, than the ($^3\text{He},d$) transition to the 3/2\textsuperscript{-} state of $^{89}\text{Y}$ could proceed by pair promotion followed by stripping, even if the $p_{3/2}$ orbital of $^{88}\text{Sr}$ were closed. Without an estimate of the strength of such two-step processes, the above estimates of the mixing in the ground states of $^{88}\text{Sr}$ and $^{90}\text{Zr}$ must be considered as tentative. (D.C. Shreve)

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2. The spin-orbit distorted wave code DWUCK, written by P. Kunz of the University of Colorado, was used in this analysis.
8. Section 1.6 of this report ($^{90}$Zr(d,d) elastic scattering).

2.9 Calculation of Absolute Spectroscopic Factors in the $^{90}$Zr(d,p) Reaction

The extraction of nuclear structure information in the form of absolute spectroscopic factors from distorted wave stripping calculations is subject to ambiguities and uncertainties in the optical model parameters used in the incoming and outgoing channels. It is often found that good fits to elastic scattering angular distributions can be obtained by many sets of optical model parameters, but the magnitudes of the calculations may differ by as much as a factor of two. However, the requirement that the spectroscopic factor remain constant with energy can serve as a criterion for choosing among the parameter sets used in a DWBA calculation. At bombarding energies in the vicinity of the Coulomb barrier one expects the DWBA description to be somewhat more reliable because stripping will occur outside the nucleus where nuclear distortions are of less importance.

To investigate the extraction of spectroscopic factors, $^{90}$Zr(d,p) reactions in a range of deuteron energies between 6 and 11 MeV have been studied. This region allows an overlap between previous data at lower \(^1\) and higher \(^2\) energies. Angular distributions from 20° to 155° were taken for the ground state and six excited states up to 3.65 MeV in excitation energy. To study highly excited states of the residual nucleus, a AE-E identifier system was used to separate protons and deuterons. Theoretical fits to the data were obtained by DWBA calculations with the zero-range code TSALLY. The optical-model parameters
used in such calculations are generated by fitting the elastic scattering differential cross sections at the appropriate energies. Because of the difficulty involved in extrapolating the optical-model parameters over a large energy range, elastic scattering angular distributions for deuterons on $^{90}Zr$ and protons on $^{91}Zr$ were taken at a variety of different energies, and optical-model fits were made to each.

 DWBA calculations have been applied to the $^{90}Zr(d,p)^{91}Zr^*$ angular distributions. As well-known ambiguities exist in fitting elastic scattering data, a family of fits was generated by using optical model parameters both from other work$^{3,4}$ and from fits to data taken here. An example of 5 such sets of data is given in Table 2.9-1 for 11 MeV deuterons and 16 MeV protons. For both the

Table 2.9-1. Optical Model Parameters.

<table>
<thead>
<tr>
<th>Set</th>
<th>$V$</th>
<th>$W_S$</th>
<th>$r_0$</th>
<th>$a$</th>
<th>$r_{01}$</th>
<th>$a_{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H,N,A</td>
<td>85.40</td>
<td>18.39</td>
<td>1.272</td>
<td>0.679</td>
<td>1.236</td>
<td>0.677</td>
</tr>
<tr>
<td>M</td>
<td>99.95</td>
<td>15.27</td>
<td>1.226</td>
<td>0.714</td>
<td>1.283</td>
<td>0.744</td>
</tr>
<tr>
<td>D</td>
<td>103.9</td>
<td>15.44</td>
<td>1.1</td>
<td>0.833</td>
<td>1.347</td>
<td>0.564</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Set</th>
<th>$V$</th>
<th>$W_S$</th>
<th>$r_0$</th>
<th>$a$</th>
<th>$r_{01}$</th>
<th>$a_{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H,D</td>
<td>51.0</td>
<td>13.6</td>
<td>1.25</td>
<td>0.65</td>
<td>1.25</td>
<td>0.47</td>
</tr>
<tr>
<td>N</td>
<td>51.0</td>
<td>14.6</td>
<td>1.25</td>
<td>0.612</td>
<td>1.25</td>
<td>0.48</td>
</tr>
<tr>
<td>M</td>
<td>54.0</td>
<td>13.7</td>
<td>1.217</td>
<td>0.623</td>
<td>1.258</td>
<td>0.48</td>
</tr>
<tr>
<td>A</td>
<td>58.0</td>
<td>13.4</td>
<td>1.10</td>
<td>0.899</td>
<td>1.34</td>
<td>0.553</td>
</tr>
</tbody>
</table>

deuteron and proton data, several families were obtained by displacing one parameter from its central value and searching on the others to obtain an optimum fit. These families were then used in the DWBA calculations. Figure 2.9-1 shows angular distributions for the 11 MeV $(d,p)$ reaction to the $d_{5/2}$ (ground), $s_{1/2}$ ($-1.21 \text{ MeV}$), and $d_{3/2}$ ($-2.06 \text{ MeV}$) states of $^{91}Zr$. All families used gave equally good fits to the experimental angular distributions; however, there are large differences in the extracted spectroscopic factors. The largest effect was seen by a change in $r_0$ from 1.1 to 1.3, for which values of $S$ from 1.04 to 1.65 were obtained. $S$ proved to be more sensitive to variations in the proton optical model parameters than in those used for the deuteron, although the shape was more dependent upon small variations in $V_d$. For lower energy deuterons, near the Coulomb barrier where nuclear distortions are weaker, the shape and fit were much less sensitive to the deuteron parameters.

As a criterion for choosing among the sets of parameters, the spectroscopic factor $S$ was required to be constant as a function of energy. Figure 2.9-2 shows the values of $S$ as a function of energy for the ground state and three excited states in $^{91}Zr$ for five different families of optical model fits. Data of Dally et al.$^1$ between 3.5 and 5.5 MeV was analyzed in the same way as the 6 to 11 MeV data and is included in this figure. (The error brackets
Fig. 2.9-1. $^{90}\text{Zr}(d,p)^{91}\text{Zr}$ angular distributions at 11 MeV for the $d_5/2$ (g.s.), $s_{1/2}(-1.21$ MeV), and $d_3/2(-2.06$ MeV) states showing DWBA fits using optical model sets enumerated in Table I.

For Set A, in which $r_{cp}$ was changed, there is a large variation in $S$ between 6 and 11 MeV. Therefore, by the above criterion Set A is not an acceptable family.

Table 2.9-2. Energy-Averaged Values of the Spectroscopic Factors *

<table>
<thead>
<tr>
<th>States</th>
<th>$^{91}\text{Zr}$</th>
<th>$S$</th>
<th>$S/1.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$d_5/2$</td>
<td>1.17</td>
<td>0.78</td>
</tr>
<tr>
<td>$-1.2$</td>
<td>$s_{1/2}$</td>
<td>1.42</td>
<td>0.95</td>
</tr>
<tr>
<td>$-2.06$</td>
<td>$d_3/2$</td>
<td>0.75</td>
<td>0.50</td>
</tr>
<tr>
<td>$-2.56$</td>
<td>$s_{1/2}$</td>
<td>0.59</td>
<td>0.39</td>
</tr>
<tr>
<td>$-3.30$</td>
<td>$d_3/2$</td>
<td>0.21</td>
<td>0.14</td>
</tr>
<tr>
<td>$-3.65$</td>
<td>$d_{3/2}$</td>
<td>0.16</td>
<td>0.11</td>
</tr>
</tbody>
</table>

* Bound state parameters of $r_{on} = 1.25$, $a_n = 0.65$; zero-range.
The energy-averaged values of $S$ for all states considered here are given in Table 2.9-2. These values are generally larger than those given in Ref. 2. However, the use of Hulthen wave-functions lowers the values in Table 2.9-2 by a factor of 1.5, bringing them into agreement with the other work.

Another major uncertainty in obtaining absolute values of $S$ is the choice of bound-state parameters. Even in stripping reactions below the Coulomb barrier in both entrance and exit channels, the absolute normalization is still dependent upon the neutron-wall parameters. (The effect of an increase in $r_{on}$ or $a_n$ is to increase the calculated cross section, or decrease $S$.) Work below the Coulomb barrier with $^{208}$Pb($d,p$) reactions, in conjunction with the requirement that the spectroscopic factors be unity, has yielded best values for $r_{on}$ and $a_n$ of 1.25 and 0.65, respectively. In the present analysis the neutron-wall was varied independently of the proton well. One might expect the effect of a variation in the neutron form factor to be more pronounced as one goes to lower deuteron bombarding energies, because the calculations are then more sensitive to normalizations in the tail of the neutron wave function as the stripping occurs in the surface of the target. Figure 2.9-4 shows such a variation in the values of $\frac{[d\sigma/d\Omega(r_{on})]}{[d\sigma/d\Omega(r_{on} = 1.25)]}$ for the range of deuteron energies considered here. Thus the determination of absolute spectroscopic factors, maintained constant with bombarding energy, is made difficult both by a selection of the appropriate family of optical model parameters and by the choice of the bound-state parameters. (J.G. Cramer, R.A. Hinrichs, D.L. Oberg and G.W. Phillips)

Fig. 2.9-3. $^{90}$Zr($d,p$)$^{91}$Zr($d5/2$) angular distributions for $6 \leq E_d \leq 11$ MeV. The DWBA fits are for Set H.

Fig. 2.9-4. Study of the variation in the cross section with the neutron bound state parameter as a function of incident deuteron energy. Case considered: $^{90}$Zr($d,p$)$^{91}$Zr($d5/2$).
2.10 A Study of Charge Exchange Effects in the $^{140}$Ce(p,d)$^{139}$Ce Reaction

Excitation functions taken at backward angles for (d,p) reactions on several nuclei\(^1,2\) have exhibited anomalous behavior at energies near the (d,n) threshold to the corresponding isobaric analogue states. Such behavior is believed to be due to a charge exchange process in the exit channel and has been reproduced in a calculation by the addition of a \(T \cdot T\) term to the proton optical potential.\(^3\) In the case of a (p,d) reaction, for example $^{140}$Ce(p,d)$^{139}$Ce, the charge exchange process appears in the entrance channel, where there is an isospin coupling between the incident proton and virtual neutron (incident upon the virtual target $^{140}$Pr\(^A\)) channels. A similar anomaly in the excitation function for this reaction might be expected near the threshold energy of the quasi-elastic $^{140}$Ce(p,n)$^{140}$Pr\(^A\) reaction, or about 15.1 MeV. Such a reaction has the advantage that the anomaly can occur in more than one exit channel at the threshold energy, as opposed to the (d,p) case where only the analogous (d,p) and (d,n) channels are coupled.

An excitation function for the reaction $^{140}$Ce(p,d)$^{139}$Ce was taken between 14.5 and 15.5 MeV in 50 keV steps at 165°, using an E-Anti identification system. Deuterons from the first three states of $^{139}$Ce were observed (the 3/2\(^+\) g.s., 1/2\(^+\) at 0.25 MeV, and 1/2\(^-\) at 0.74 MeV). A multiplier E-E identification system was later used and several points in the excitation function were repeated. These are all combined in Fig. 2.10-1. Within the 5% statistics obtained, no anomaly was observed in the (p,d) reaction leading to the ground state and first two excited states of $^{139}$Ce. Fig. 2.10-1 also shows DWBA calculations of the code TSALYL which seem to re-produce the overall shape of the experimental excitation function for the two excited states but is too steep for the ground state transition. (P. von Brentano, J. G. Cramer, R. Heffner, R. Hinrichs and F. Richard)

2.11 The $^{208}\text{Pb}(p,n)$ and $(p,2n)$ Reactions

In a recent study of the resonant $^{208}\text{Pb}(p,p'\gamma)$ reaction in which gamma-ray spectra were studied with a Ge(Li) counter, we have observed gamma rays from the de-excitation of $^{207}\text{Bi}$ and $^{208}\text{Bi}$. The fact that these gamma rays are strong and easily observable suggests that they could be employed in studying the $(p,n)$ and $(p,2n)$ cross sections of $^{208}\text{Pb}$ as a function of energy. Such data would be useful in obtaining neutron partial-widths for $^{208}\text{Bi}$. Figure 2.11-1 shows a typical gamma-spectrum. Plans are now being made for excitation functions to study these gamma rays. (W.J. Braithwaite, J.C. Cramer, H. Ejiri, S.M. Ferguson, G.W. Phillips and P. von Brentano)

Fig. 2.11-1. Gamma-ray spectra from $^{208}\text{Pb} + p$.

2.12 The $^{90}\text{Zr}(\alpha,^3\text{He})^{91}\text{Zr}$ Reaction at 42 MeV

Alpha particle stripping as a tool for nuclear spectroscopy, as opposed to deuteron stripping, has been used very little, mainly because of its high negative Q values, the greater difficulty in particle identification, and the greater complexity in any theoretical calculations. For a comparison with $(d,p)$ reactions on the Zr isotopes (as carried out on the Van de Graaff - see Sec. 2.9) the cyclotron is being used for a study of the $(\alpha,^3\text{He})$ reaction on these isotopes. An angular distribution between 25° and 75° for the $^{90}\text{Zr}(\alpha,^3\text{He})$ reaction.

| Table 2.12-1. Optical Model Parameters, $^{90}\text{Zr}(\alpha,^3\text{He})$. |
|------------------|-----------------|-------|------|----------|------|------|------|
| $\alpha$         | $V$             | $W_V$ | $r_0$ | $r_{0I}$ | $a$  | $a_I$ | Ref. |
| $^3\text{He}$    | 147.75          | 18.95 | 1.42  | 1.42     | 0.557| 0.557 | 4    |
|                  | 114.85          | 8.70  | 1.064 | 1.856    | 0.876| 0.692 | 5    |
was taken at 42 MeV by use of a $\Delta E-E$ identification system. Figure 2.12-1 shows this angular distribution to the $d_{5/2}$ ground state and $g_{7/2}$ third excited state ($\sim 2.21$ MeV) in $^{91}$Zr. (Other states were quite weakly excited and are not shown.) DWBA calculations with the code TSALLY, using the optical model parameters of Table 2.12-1, are also included. We can write the experimental cross section as

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{2J_F + 1}{2J_i + 1} \frac{NR}{2S + 1} S \sigma(\theta)$$

where $\sigma(\theta)$ is the reduced cross section calculated by TSALLY, $S$ is the spectroscopic factor for the state, and $N$ is a factor which accounts for the overlap of the particle and the $n-^{3}$He system as well as the strength of the interaction. A value of $N = 6.53$ is obtained by assuming the interaction is given by the potential between the neutron and $^{3}$He and by using the asymptotic form of the wave function obtained from the solution of Schrodinger's equation with a binding energy equal to that of the neutron in the alpha particle. $R$ is an additional normalization factor to account for the simplifications made in these calculations. ($R$ and $N$ are expected to remain constant with energy.) The factor $R$ has been determined in previous $(a, ^{3}$He)$^1$ and $( ^{3}$He, $a)$ experiments to be about 24, although it has ranged from 5 to 36 as a function of energy and optical model parameters. By using spectroscopic factors of 0.75 for the ground state and 0.52 for the $g_{7/2}$ state, with the optical model parameters listed in Table 2-12.1 (and $\rho_{0} = 1.2, a_{n} = 0.7$), $R$ was found to be 8.0 and 17.1, respectively. (Such a discrepancy in the value of $R$ for different states in the residual nucleus was also seen in the $^{90}$Zr$(a, ^{3}$He) work of Reference 1.) Continuation of this work, both in extending the angular distributions and in varying the sets of optical model parameters to establish a better fit, is in progress.

(J.C. Cramer and R. A. Hinrichs)
4. D.C. Shreve (private communication).
3. ISOBARIC ANALOGUE STATES

3.1 Search for a \( T = 5/2 \) Resonance in \( ^{41}\text{Sc} \) via \( ^{40}\text{Ca}(p,p) \)

Isobaric analogue states differing by two units of isospin (\( T \)) from the ground states have been observed through \( T \)-allowed reactions, and proton resonances with \( T = T_2 + 1 \) and \( T_2 + 2 \) have been investigated through \( T \)-violations of one unit. The work recounted here is an attempt to observe a \( T = T_2 + 2 \) state as a resonance in proton-induced elastic scattering on a self-conjugate target nucleus and thus to find a \( T \) violation of two units (actually a four-times forbidden reaction; twice forbidden in formation and twice forbidden in decay). If found, the cross-section and width of the resonance would provide information concerning the relative strength of the isotensor portion of the Coulomb interaction in nuclei.

If the Coulomb potential is written in isospin notation it may be separated into three parts:

\[
E_c = \frac{e^2}{r_{1,j}} \sum_{i<j} \left\{ \left( \frac{1}{4} + \frac{1}{3} \text{ } t_{i}^{1} \cdot t_{j}^{1} \right) - \frac{1}{2} t_{3}^{1} t_{3}^{i} + t_{3}^{j} \right\} \left( t_{3}^{i} t_{3}^{j} - \frac{1}{3} t_{1}^{1} \cdot t_{j}^{1} \right).
\]

The first is an isoscalar part, which contributes a fixed energy to the state. The next is an isovector part, which tends to mix states differing by one unit of \( T(\Delta T = 1) \). It is through this term that previously studied \( T \)-violating reactions to isobaric analogue resonances are presumed to have gone. The third term, the isotensor part, contributes to mixing of states differing by one or two units of isospin (\( \Delta T = 1 \) or \( \Delta T = 2 \)). It is via the \( \Delta T = 2 \) portion of this term that our expected resonance should be reached.

Three requirements would seem to be necessary for the success of this experiment. First, one would want a nucleus with large \( Z \) so that the isotensor term, and thus the \( \Delta T = 2 \) mixing, would be as large as possible. Second, in order that the energy of the excited state sought might be readily and accurately calculated, one would like to work with mirror nuclei in the compound system, i.e. a self-conjugate target. The third consideration is that the formation of the compound system be favored by the configuration of the shell model. All three of these requirements are well satisfied by \( ^{40}\text{Ca} \). Not only is it a self-conjugate nucleus but recent calculations show it to have the largest amount of isospin mixing of any stable nucleus. This mixing is a direct measure of the isovector and isotensor strengths. Also, \( ^{40}\text{Ca} \) has been reported to have considerable mixing of the desired \( (f_{7/2})^2 \) configuration in its ground state.

With a \( ^{40}\text{Ca}(p,p) \) reaction we are probing the compound nucleus \( ^{41}\text{Sc} \) and looking for analogues of states in \( ^{41}\text{Ar} \). (See Fig. 3.1-1) Work done at Duke shows that both the 4th and 6th excited states of \( ^{41}\text{Ar} \) have strongly resonating analogues in \( ^{41}\text{K} \). This work also provides an experimental determination of the \( T = 3/2 \) to \( T = 5/2 \) energy shift in the \( A = 41 \) isobar (\( E_2 \) in Fig. 3.1-1). Further information is obtained from recent work at Heidelberg on the resonance reaction \( ^{40}\text{K}(p,p) \) which adds the experimental determination of the \( T = 1/2 \) to \( T = 3/2 \) energy shift (\( E_1 \) in Fig. 3.1-1).
Excitation functions in the 14 MeV region have been taken with 1 keV energy steps over a total of nearly 100 keV and with 5 keV steps over about 300 keV. The output of four detectors (at 90°, 125°, 146°, and 170°) is stored in the on-line computer system and partially analyzed there. To date, the results have been inconclusive, a possible result of the expected narrowness of the state. All indications would imply a width of a few keV or less.

Work at present is aimed toward overcoming target thickness and inhomogeneity problems and achieving better beam energy resolution and stability of energy variation through use of an accelerating-decelerating voltage on the target. (D.D. Chamberlin and J.G. Cramer)

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### 3.2 Proton Decay of Isobaric Analogue States Formed in the (d,n) Reactions

The experimental study of the (d,np) reaction reported last year has been concluded. A preliminary report has been published and a manuscript describing the complete work has been prepared for publication.

In addition to the targets listed in the previous report, carbon and oxygen targets were also investigated, since most targets contain these elements as contaminants. The main purpose was to ascertain that the (d,n) events or other sequential proton events from these contaminants would not be misidentified as (d,np) events from the targets of interest.
For the carbon target, no discrete-energy sequential proton events are discernable in the energy range studied. For the oxygen target, only one such group is seen as illustrated in Fig. 3.2-1. This proton group labeled as S and having a peak energy of 4.11 MeV can reasonably be identified as the sequence $^{16}\text{O}(d,n)^{17}\text{F}^2_1 (3/2^+, 5.815\text{ MeV}) \rightarrow p + ^{16}\text{O}\text{(g.s.)}$. The extracted cross sections are

![Proton LAB ENERGY (MeV)](image)

**Fig. 3.2-1.** Pulse height spectra of protons from the $^{16}\text{O} + d$ reaction.
displayed in Fig. 3.2-2 for the various incident energies.

The majority of the targets investigated either have an insignificant amount of oxygen contaminants or do not have (d,np) transitions which overlap the $^{185}$O(d,np) group, except for $^{88}$Y and $^{94}$Zr. Specifically, the previously identified transitions: $0^+$(1.214 MeV)-IAS $\rightarrow$ 5/2$^-$(1.75 MeV)[P$^0_5$] in the $^{88}$Y (d,np) study and 5/2$^+$ (g.s.)-IAS $\rightarrow$ 2$^+$ (0.916 MeV)[P$^0_5$] in the $^{94}$Zr(d,np) study are now calculated to be largely due to contributions from the $^{16}$O(d,np) events. The corresponding excitations shown in Figs. 10.1b and 10.1c of Ref. 1 are then essentially that of the $^{16}$O(d,np) transition. Consequently, it can now be said that all measured excitation functions for the cases A > 16 exhibit a similar shape in which there is a sharp rise in the cross section above threshold followed by a slow decrease as the energy is increased.

The above corrections however do not affect the earlier analysis$^1$ of the (d,np) cross section systematics and the conclusions drawn since they were based on the study of the Zr, Mo, and Sn isotopes and only on the data of the transitions to the ground state of the final nucleus.

Additional analysis on the cross section systematics have also been made:

a. The enhancement factors $F$ (see Eq. 4 of Ref. 1) for the ground state transitions of the (d,np) reactions on $^{27}$Al, $^{64}$Ni, $^{66}$Zn, $^{80}$Y, $^{90}$Zr, and $^{206}$Pb have been calculated for cases where the statistical and spectroscopic factors are known. The variations in the enhancement factors are also seen to account for the large variations in the (d,np) cross sections. This consistency further supports the importance of considering the decay through the spreading width $\mathcal{W}$.

b. For the transitions to excited final states, the small (d,np) cross sections are generally consistent with Eq. 4 of Ref. 1. In other words, the branching ratios to excited states are generally smaller than the branching ratios to ground states even when the neutron decay channels are open.

Further insights into the (d,n) formation mechanism have also been obtained and we will discuss this briefly. For the $d_{5/2}$-IAS to $0^+$ transitions in the (d,np) study on $^{90}$Zr and $^{92}$Mo, accurate angular distribution data at the various bombarding energies are available. From these, the m-substate population of the $d_{5/2}$-IAS can be extracted if one assumes a sequential process for the (d,np) reaction. The extracted m-substate fractions are shown in Fig. 3.2-3. One interesting point to note is the value of the $f_{1/2}$ fraction extrapolated to essentially threshold energy. It is $f_{1/2} = 0.72 \pm 0.06$. This value implies that the neutron spin flip probability, $P_f$, is 0.42 $\pm$ 0.09. Specifically, $P_f$ is defined as the probability for the outgoing neutron to have a spin orientation opposite to that of the neutron in the incoming deuteron. The above follows from the relation $P_f = 3/2(1 - f_{1/2})$ which can be derived from a consideration of angular
momentum conservation provided the following two conditions are satisfied:

a. all outgoing neutrons following the (d,n) reaction are s-wave and b. the D-wave component of the deuteron wave function can be neglected. The value 0.42 for $P_F$ suggests that spin-orbit interactions should be taken into consideration if the IAS formation proceeds through a direct stripping process.

The $m$-substate populations $f_m$ are seen to change monotonically with bombarding energy. Since these $f_m$ determine the angular distribution of the decay protons, we can convert the measured $(d,n)$ excitation functions of the $d_5/2$-IAS $\rightarrow 0^+$ transitions into angle integrated values $\sigma(d,n)$. These $\sigma(d,n)$ for transitions from $\mathrm{^92\text{Nb}}^{*}$ and $\mathrm{^93\text{Tc}}^{*}$ are shown in Fig. 3.2-4 which essentially illustrates the energy dependence of the $(d,n)$ formation cross sections $\sigma(d,n)$.

A careful examination of the threshold dependence of the $\mathrm{^92\text{Mo}}(d,n)\mathrm{^93\text{Tc}}^{*}$ $(d_5/2$-IAS) cross-section yields some general qualitative features which the transition amplitude $T$ for the $(d,n)$ reaction must satisfy. Referring to Fig. 3.2-5, it is seen that the cross section exhibits a $k_n/k_d$ dependence (where $k_n$ and $k_d$ are the wave numbers of the outgoing neutrons and incoming deuterons respectively) which implies that the value of the transition amplitude $T$ is relatively large and changes slowly with bombarding energy. In a direct one-step stripping process, $T$ is essentially zero at threshold and the requirement on $T$ is that it rises to a large value within $\sim 100$ keV. Clearly such a drastic change in the transition amplitude is hard to conceive in a simple direct stripping mechanism. The recent proposal of Zaidi and Brentano$^{3,4}$ which suggest the inclusion of a charge exchange potential (for the outgoing nucleon channel) in the distorted wave stripping theory may account for such an energy dependence for the transition amplitude. However, no detailed calculations were undertaken and therefore no definite conclusion can be made. Suffice it to say that the present $(d,n)$ data do not in general exhibit similar detailed dependence on the bombarding energy (see Fig. 3.2-4). Further, because the charge-exchange coupling affects the $(d,p)$ channel (leading to the corresponding parent analog) as well, it is necessary to consider simultaneously the effects on the $(d,p)$ channel$^4$ and the $(d,n)$ channel in order to completely assess the importance of the charge exchange process. (J.S. Blair, N. Cue, C.C. Ling, and P. Richard)

Fig. 3.2-4. The angle integrated (d, np) cross sections corresponding to the ground state transitions from the d5/2 (g.s.) - IAS in 92Mo and 95Tc. The closed circles are the values estimated from the 170° cross sections utilizing the m-substate fractions shown in Fig. 3.2-3, while the open circles are those obtained from the measured angular distributions.

3.3 Isobaric Analogue States of 93Mo

We have studied proton elastic and inelastic scattering on a 92Mo target with the purpose of investigating the decay properties of the Isobaric Analogue States (IAS) in 93Tc formed as compound nucleus resonances. The inelastic scattering is particularly interesting since it gives information about the overlap between the wave function of the IAS in 93Tc and the excited states in 92Mo. This information corresponds to that obtained by doing a (d, p) reaction on the 92Mo target in the excited states, which is very difficult if not impossible to do experimentally.

In this investigation protons from the FN Tandem are scattered off a
metallic target of enriched $^{92}$Mo and detected at several angles simultaneously by laboratory-built Si(Li) solid-state detectors. The analysis of each spectrum is facilitated by the use of a peak-summing program processed by the SDS 930 computer system in the laboratory.

In the elastic scattering excitation function (see Fig. 3.3-1) the Coulomb plus the resonance scattering amplitudes give rise to interference patterns, whereas in inelastic scattering the resonances manifest themselves as sharp spikes superimposed on backgrounds which are rising with incident proton energy (Fig. 3.3-2a and b). The total width and resonance energy of each IAS is extracted from the inelastic excitation functions by fitting the data to an energy-dependent background plus Breit-Wigner resonance formula; target thickness is duly accounted for. Knowing the total width, the proton elastic width is then derived by fitting the elastic scattering excitation functions with an isolated resonance plus optical potential scattering prescription.

Closely spaced IAS which show up in elastic scattering excitation function are unveiled much more distinctly in the inelastic scattering yield curve, due to the absence of interference with optical potential scattering. Furthermore, an IAS that has a large overlap with one of the excited states may show up more clearly in the excitation function of that inelastic channel than in the elastic yield curve. The resonance observed at $E_p = 6.09$ MeV affords such an example; this particular IAS shows up very weakly in the elastic scattering excitation function. Another interesting point is that there are IAS that resonate at slightly different energies in different outgoing channels. For example the resonance energies for the different channels pertaining to the group around $E_p = 5.8$ MeV are:

![Fig. 3.3-1. Excitation functions of elastically scattered protons from $^{92}$Mo + p.](image1)

![Fig. 3.3-2a,b. Excitation functions of inelastically scattered protons from $^{92}$Mo + p. The solid lines have no theoretical significance.](image2)
$4^+(E_R = 6.790 \text{ MeV}), 2^+(E_R = 6.904 \text{ MeV}), 5^{-}(E_R = 6.84 \text{ MeV})$; another similar group is at $E_R = 7.8 \text{ MeV}$. The 6.8 MeV group seems to indicate that two closely spaced IAS are contributing in different proportions to the different outgoing channels.

Angular distributions of the inelastically scattered protons have been obtained at energies on and off resonances. Some of the angular distributions for the inelastic scattering to the $2^+$ state (1.52 MeV), $5^{-}(2.52 \text{ MeV})$ and $3^{-}(2.88 \text{ MeV})$ are given in Figs. 3.3-3 and 3.3-4. Ideally, these would allow one to extract the total reaction cross section of each channel, and in turn the sum of the proton partial widths of each IAS. The extraction of total resonant cross sections allows one to obtain the partial widths in a simple manner, however, only if the interference between resonant and direct reaction amplitudes is unimportant or if direct reaction contribution to the nonresonant cross section is negligible. Since the nonresonant part of the excitation function contributes more than one-third of the total cross section at resonant energies, the above restriction is particularly stringent in our case.

We have made Hauser-Feshbach calculations for the energy and angle dependence of the cross section up to 8 MeV incident proton energy. The calculated energy dependence when normalized by a constant factor agrees very well with the energy dependence of the background cross section (Fig. 3.3-5). The angle dependence (not normalized) together with a DWBA prediction is compared to the data in Fig. 3.3-6. The DWBA predictions, as well as being very small, have large anisotropy (ratio of 180° to 90° cross section as large as 4). The Hauser-Feshbach calculations, on the other hand, predict approximate isotropy and absolute cross section to within a normalization constant. The normalization factor is always smaller than 1 (between .5 and .75); this is consistent with the fact that not all outgoing channels are considered in the calculation. It is worth pointing
Fig. 3.3-5. Comparison of data and theoretical predictions of excitation functions. Solid lines are normalized results of a Hauser-Feshbach calculation. Dotted lines are DWBA calculations given in absolute cross sections.

out however that the Hauser-Feshbach normalization is not the same for all exit channels.

The above considerations indicate that in most cases the resonance-direct interference is weak, although it cannot be ruled out completely. This is especially true below the Coulomb barrier (≈ 7 MeV); hence the extracted cross section for resonances below and around E_p = 7 MeV is deemed to be accurate. The cross section of each inelastic channel is obtained by taking the difference between on and off resonance angular distributions; the integration is done from 90° to 180°. The sum of the proton partial widths to each channel is then given by:

\[
\sum_{\ell', j'} \Gamma_{p'\ell'j'} = \frac{2}{\pi} \frac{2}{} \frac{\sigma_{pp'}}{r_p} \frac{(E_{p'} - E)^2 + \Gamma^2/4}{\chi^2(2J + 1)}.
\]

Fig. 3.3-6. Angular distributions: comparison of data with (a) Hauser-Feshbach predictions (solid lines, unnormalized) and (b) DWBA calculations (dotted lines, in absolute cross sections).
The results of these and further analyses presently under way will be presented in a future publication. (N. Cue, R.H. Heffner, C.C. Ling, and F. Richard)


3.4 Identification of $^1$-Neutron Particle-Hole States in $^{140}$Ce

In a recent experiment it has been shown that the low-lying analogue resonances in $^{141}$Pr decay strongly and selectively to groups of neutron particle-hole states in $^{140}$Ce. This section describes a study of the reaction $^{140}$Ce($p,p'\gamma$)$^{140}$Ce, which we have used to investigate the gamma-ray decay of the neutron particle-hole states in $^{140}$Ce populated by the $f_{7/2}$($9.74$ MeV) and $p_{3/2}$ ($10.40$ MeV) analogue resonances in $^{141}$Pr. The reaction is shown schematically in Fig. 3.4-1. Inelastically scattered protons from a natural Ce target (88% $^{140}$Ce) were detected with a cooled Si(Li) counter in coincidence with gamma rays detected with a 3"x3" NaI(Tl) crystal. An effective solid angle of about 430 mstr was subtended by the crystal. Energy windows on the gamma-ray spectrum were set at 2.6-5.0 MeV for the $f_{7/2}$ resonance and 3.3-5.0 MeV for the $p_{3/2}$ resonance to select ground-state transitions over cascades through other levels. In the former case a window of 0.6-1.8 MeV was also employed to observe gamma-ray branches through the $2^+$($1.5$ MeV) first excited state. Singles and coincidence proton spectra were obtained for proton counter angles of 90°, 140°, and 155°. From these data we have obtained the ground-state branching ratios for the various neutron-particle-hole states observed. Efficiencies were obtained by a comparison of the $^{140}$Ce coincidence yields with the yield from the $^{12}$C($4.43$ MeV + g.s.) reaction. Since the gamma-ray counter spanned an angle of about 43° in the reaction plane, the angular correlation factor $W$ will be quite strongly

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Fig. 3.4-1. Schematic picture of the reaction $^{140}$Ce($p,p'\gamma$).
Fig. 3.4-2. The figure shows the cross sections to neutron particle-hole states in the reaction $^{140}$Ce(p,p')$^{140}$Ce at $\theta = 90^\circ$. Also shown are the branching ratios for the gamma decay of the neutron particle-hole states with excitation energy $E_x$ to the $0^+$ ground state. Also shown is the sum of the branching ratios for all gamma rays through the $2^+(1.6$ MeV) state.

In this experiment, if we make the assumption that the negative-parity neutron particle-hole states in the closed shell nucleus $^{140}$Ce decay to the ground state by E1 radiation only. The neutron particle-hole states populated from the $f_{7/2}$ resonance have the dominant configurations ($f_{7/2},s_{1/2}^2$) and ($f_{7/2},d_{3/2}^2$), which can couple to spins 2$, 3$, 4$, or 5$. Our assumption predicts that none of these will decay strongly to the ground state, and this agrees with the data. The particle-hole states populated in the $p_{3/2}$ resonance have the dominant configurations ($p_{3/2},s_{1/2}^2$) and ($p_{3/2},d_{3/2}^2$). These contain two $1^-$ states. Our assumption then predicts two strong ground-state branches, which were observed for states at excitation energies $E_x = 4.18$ and $4.37$ MeV, and to which we therefore assign spins $J^m = 1^-$. Some of the non-vanishing branches observed in the $3/2^-$ resonance may be due to the decay of other $1^-$ levels, since the particle-hole states in the $3/2^-$ resonance are strongly fragmented, and the proton peaks in the spectrum are actually unresolved groups of levels.

We must examine more carefully the above assumption, which implies for example, that a $2^-$ state will decay preferentially by E1 radiation to the $2^+(1.6$ MeV) state or to some higher state and that the M2 branch to the ground state will be very weak. Indeed, the Weisskopf estimates for single-particle transitions strongly favor the decay to the $2^+$ states ($\Gamma(M2)\approx 0/\Gamma(E1)\sim 5 \times 10^{-6}$). The higher order multipoles are inhibited even further for a neutron transition by the effective charge of the neutron, which leads to reduction by factors of $1/A^2$ and $1/A^4$ for E2 and E3 radiation respectively. Of course, in addition to the single particle estimates the nuclear matrix elements may have an important effect on the branching ratios. However, single neutron states built on the $2^+(1.6$ MeV) state in $^{140}$Ce are known to be appreciably mixed into the $f_{7/2}$ and averaged and is expected to be near unity. Figure 3.4-2 shows the values of BW extracted from our measurements at a proton angle of $90^\circ$, and it is seen that the various states have quite different branching ratios. The branching ratios for the other proton angles were similar to the values at $90^\circ$. The error bars shown in Fig. 3.4-2 are estimated from statistical errors and errors due to background correction. There is, however, an uncertainty in the correction for sum coincidences, which may increase the errors for the weak branches by about a factor of 2. The absolute normalization is uncertain to $\pm 50\%$.

Kinsey and Bartholomew have given evidence from neutron capture reactions that high-lying states with neutron configurations in heavy nuclei decay predominantly by E1 radiation. We can understand the striking differences in the gamma-ray branching ratios observed in this experiment.
P3/2 parent analogue states in $^{144}\text{Ce}$, and we can expect a similar admixture into the neutron particle-hole states in $^{140}\text{Ce}$. Therefore the nuclear matrix elements of the two branches should not be too different in magnitude.

In conclusion we want to emphasize two important aspects of this experiment: (a) The proton decay of the analogue resonances selects high-lying neutron particle-hole states. (b) These particle-hole states contain admixtures of particle-hole states built on low-lying collective states. It is under these circumstances that we can assign a spin $J^T = 1^-$ to those particle-hole states which have a strong gamma-ray branch to the ground state, and it is these conditions which distinguish this experiment from an otherwise similar one on $^{60}\text{Ni}(p,p'y)_{0}^{60}\text{Ni}$.\(^{5,6}\)


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3.5 Two-Neutron-Hole Configurations of $^{206}$Pb from Isobaric Analogue Measurements

Angular distributions and excitation functions for the proton scattering from the isobaric analogue states of $^{207}$Pb to the low lying levels of $^{206}$Pb which were reported in the 1966 and 1967 Annual Reports are used to obtain the two-neutron-hole configurations for five of these states. The results are compared to the theoretically calculated shell model configurations\(^{1,2}\) based on two interacting neutron holes in the $^{206}$Pb core. Previous spectroscopic information about $^{206}$Pb is based on stripping and pickup experiments.\(^{3,4}\) Recently, two-neutron transfer reactions leading to $^{206}$Pb were studied,\(^{5}\) but cross section predictions for these reactions depend upon the wave functions in a complicated fashion making it difficult to deduce them from the measurements. The present results are of particular interest since they provide information, independent of nucleon transfer reaction theories, which can be compared directly with shell model calculations.

In proton scattering on $^{206}$Pb forming the IAS of a neutron-hole state $J^T = 1^-$ of $^{207}$Pb as a resonance in the $^{207}$Bi compound system, we are able to study final states in $^{206}$Pb which have two-neutron-hole configurations ($J^T = 1^-$, $J^T = 1^-$), where $J^T$ is the second neutron hole and $T$ is the spin of the final state. If a $^{206}$Pb wave function is expressed as a sum over two-hole configurations, such as
\[ y_I = \sum_{j} c_{j}^{I} (j^{-1}, j^{-1})_{I} \]  

then for the decay of a hole state \((j^{-1})\) with outgoing particle \(j\), the inelastic width may be written as

\[ \Gamma_{p'} = \sum_{j} \frac{2I + 1}{2J + 1} \frac{1}{2j} \sum_{j} \Gamma_{j}^{mod} \left(c_{j}^{I}\right)^{2} \]

where \(j \neq J\). For \(j = J\) the numerator is multiplied by 2. The quantities \(\Gamma_{j}^{mod}\) are single-particle decay widths from the \(j\) shell model orbital, and our technique for analysis rests on the choice for their values. At this stage of the development of the theory for inelastic scattering via analogue resonances, we regard the experimental single-particle widths obtained from the decay of the IAS of the \(^{208}\)Pb ground state to the hole states in \(^{207}\)Pb as measured in the \(^{207}\text{Pb}(p,p')\) reaction \(^{6,7}\) as the best values to use for \(\Gamma_{j}^{mod}\). This procedure avoids the uncertainties inherent in theoretically calculated single-particle widths. It rests, rather, on two assumptions for which there is ample experimental evidence \(^{3,8}\): (a) a good closed shell for \(^{208}\text{Pb}\) and (b) pure one-hole configurations in \(^{207}\text{Pb}\).

The squares of the amplitudes (defined in Eq. 1) in the \(^{206}\text{Pb}\) wave functions are derived from the experimental total inelastic widths (Eq. 2), and are listed in Table 3.5-1. Only two-hole configurations based on the \(^{1}P_{1/2}, f_{5/2}^{1}\) and \(^{3}P_{3/2}\) orbitals were considered in the analysis. From the single-hole energies in \(^{207}\text{Pb}\), it is unlikely that other orbitals are important below 2 MeV excitation in \(^{206}\text{Pb}\).

The values of \(\Gamma_{j}^{mod}\) used in Eq. 2 were obtained by averaging the experimental results for \(^{207}\text{Pb}(p,p')\) at the \(^{208}\text{Pb}\) g.s. analog. \(^{6,7}\) They are: for \(^{1}P_{1/2}\), 31 keV at 11.49 MeV; for \(f_{5/2}^{1}\), 3 keV at 10.92 MeV; and for \(^{3}P_{3/2}\), 12 keV at 10.60 MeV. Small corrections to these numbers were made for the slightly different energies in the present experiment by assuming that \(\Gamma_{j}^{mod}\) is proportional to the transmission coefficient \(T_{j}\) and by using the tabulated values of \(T_{j}\) by Mani et al. \(^{3}\).

The reason for the large difference between \(\Gamma_{mod}^{1}\) and \(\Gamma_{mod}^{3}\) obtained in both Ref. 6 and 7 is not presently understood. It could imply that there are difficulties in extracting the elastic resonance width \(\Gamma_{mod}^{1}\) at the \(^{208}\text{Pb}\) g.s. analogue, which would then affect the values of \(\Gamma_{mod}^{3}\) and \(\Gamma_{mod}^{f_{5/2}}\). It should be emphasized, however, that this problem would not affect the results in Table 3.5/1, with the exception of the excited \(0^{+}\) state. The coefficients for the other states all depend on products of the above \(\Gamma_{j}^{mod}\) which are accurately determined from the \(^{207}\text{Pb}(p,p')\) experiment.

The 1.34 MeV \(3^{+}\) state was taken to have a pure \((^{1}P_{1/2}, f_{5/2}^{1})\) configuration in order to obtain an overall normalization. The validity of this is suggested by the excitation function \((p, 18, 1967 \text{ Annual Report})\), by the theoretical calculations \(^{1,2}\) and by the recent \((d,t)\) experiment. \(^{4}\) Use of this normalization limits the uncertainties in the configurations of the other states to the values
Table 3.5-1. Values of \((c_1)\) in the \(^{208}\text{Pb}\) Wave Functions

<table>
<thead>
<tr>
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<th>Experimental</th>
<th>Theoretical (a)</th>
</tr>
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|                  | \[ \begin{align*} 
0^+ \text{ g.s.} & \quad 0.05^{a} (0.13) \, p_{1/2}^{-2} + 0.25^{b} (0.07) \, f_{5/2}^{-2} + 0.20^{a} (0.08) \, p_{3/2}^{-2} \\
 & \quad 0.54 \, p_{1/2}^{-2} + 0.20 \, f_{5/2}^{-2} + 0.12 \, p_{3/2}^{-2} \text{ (b)} \\
 & \quad 0.57 \, p_{3/2}^{-2} \text{ (c)} \\
2^+ 803 \text{ MeV} & \quad 0.68 \, f_{1/2}^{-1} + 0.22 \, p_{1/2}^{-1} \, p_{3/2}^{-1} \text{ (c)} \\
0^+ 1.15 \text{ MeV} & \quad 0.22^{a} (0.05) \, p_{1/2}^{-2} + 0.78 \, f_{5/2}^{-2} + 0.39 \, p_{3/2}^{-2} \\
 & \quad 0.48 \, f_{1/2}^{-2} \text{ (c)} \\
3^+ 1.34 \text{ MeV} & \quad 1.00 \, p_{1/2}^{-1} \, f_{5/2}^{-1} \\
 & \quad 1.12 \, f_{1/2}^{-1} \text{ (c)} \\
2^+ 1.47 \text{ MeV} & \quad 0.39^{a} (0.10) \, p_{1/2}^{-1} \, f_{5/2}^{-1} + 0.61^{a} (0.18) \, p_{1/2}^{-1} \, p_{3/2}^{-1} \\
 & \quad 0.86 \, p_{1/2}^{-1} \, f_{5/2}^{-1} \\
4^+ 1.69 \text{ MeV} & \quad \text{---} \text{ (e)} \\
1^+ 1.71 \text{ MeV} & \quad 1.00^{a} (0.10) \, p_{1/2}^{-1} \, f_{5/2}^{-1} \\
 & \quad 1.02 \, p_{1/2}^{-1} \, p_{3/2}^{-1} |

a. W.W. True, to be published. In some cases very small amplitudes have been omitted.
d. Resonances were observed implying \(p_{1/2}, f_{5/2}\), and \(p_{3/2}\) contributions. These were not analyzed because of substantial interference and contributions from direct scattering.
e. Resonances for this state were not observed.
shown in Table 3.5-1. An alternate approach, independent of any normalization, would have created greater uncertainties by its dependence on both the absolute values of $\Gamma^{mod}$ and the extraction of the elastic resonance widths (the latter being subject to the difficulty mentioned above).

Results from the most recent shell model calculation by True are compared in Table 3.5-1 with the experimentally determined wave functions. The theoretical column gives the energies and wave functions for the first seven predicted states in $^{206}$Pb, and the experimental column shows that at least five are in excellent agreement with the measurements. If the known 4$^+$ state at 1.68 MeV is similar to the predicted 4$^+$ state at 1.60 MeV, then resonances for this state would not have been observed. This is consistent with our assigning the resonances in the cross section entirely to the 1$^+$ state at 1.71 MeV which, as Table 3.5-1 shows, is then in accord with the predicted 1$^+$ state.

The conclusions drawn from the results presented here may be summarized as follows:

a. The low energy structure of $^{206}$Pb appears to be well described in terms of two neutron holes moving in the shell-model potential of the $^{208}$Pb core.

b. It is possible to extract quantitative spectroscopic information from inelastic scattering at isobaric analog resonances, in a relatively easy manner, at least in those regions of the periodic table where the simple shell model provides a good description.

(C.D. Kavaloski, J.S. Lilley, P. Richard, and N. Stein)


3.6 Proton Decay of the Single Neutron Analogue States in $^{209}$Bi

Proton inelastic scattering to isobaric analogue states (IAS) gives information on the overlap of the IAS with the final state. In the case of the IAS of one of the single neutron states of spin J in $^{209}$Pb the overlap is determined by the neutron particle-hole configurations of the final state I which are of the form $(Jj^{-\frac{1}{2}})I$, where $j$ is the spin of the various neutron holes. The purpose of this work is to obtain information on the strength of the particle-hole con-
figurations and the spins of the final states in $^{208}$Pb by observing the angular distributions of the decay protons from the $^{208}$Pb IAS. The angular integrated cross sections determine the total inelastic widths $\Gamma_p^{I}$, which are related to the parentage coefficients $a_{ij}^P$ of the neutron particle-hole configurations and the single particle widths $\Gamma_j^{SP}$ by

$$\Gamma_p^{I} = \frac{2 I + 1}{2 J + 1} \sum_{ij} a_{ij}^P \Gamma_j^{SP}$$

$\Gamma_j^{SP}$ values were taken from experiment.\textsuperscript{2,3}

Proton beams were obtained from the 3-stage FN tandem Van de Graaff accelerator. The measurements consist of proton spectra taken on-resonance at lab angles between 60° and 170°. In addition to the angular distributions, excitation functions were measured in order to accurately determine the total widths and resonance energies of the analog resonances (see Sec. 3.7). An on-resonance spectra for the $d_5/2$ (1.56 MeV analog) resonance is shown in Sec. 10.9. These

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**Fig. 3.6-1.** Angular distributions for the inelastic scattering of protons ($E_p = 14.91$ MeV) from $^{208}$Pb at the position of the $g_9/2$ analogue resonance in $^{209}$Bi. The final-state excitation energy and spin of each (if known) are given. In the case of the 4.475 MeV 6$^-$ state, the solid curve is a calculation based on ($g_9/2$, $p_3/2$) configuration with spin 6$^-$. The other curves are best fit to an even Legendre polynomial series up to $P_4$.

**Fig. 3.6-2.** Five angular distributions at $E_p = 14.91$ MeV for different final states in $^{208}$Pb. The two 5$^-$ states are fits with ($g_9/2$, $p_3/2$) 5$^-$ calculated shapes. The magnitudes are adjusted to fit the data. The curve through the 4$^-$ at 4.351 MeV is for the calculated cross section for ($g_9/2$, $p_3/2$) 4$^-$. Spectra were measured with laboratory-made, cooled Si(Li) detectors (see Sec. 10.9). Magnets were placed in front of the detectors in order to deflect electrons emanating from the target. In addition, $\simeq 300$ μg/cm$^2$ Au foils were placed in front of each detector. In this configuration the energy resolution obtained was 26–32 keV. Thin self-supporting metal foils were used for targets and care
Fig. 3.6-3. Proton partial widths for the decay of analog resonances in $^{209}$Bi.

was taken to eliminate light-element contaminants. The output signals from the amplifier-biased amp systems were fed into ADCs and subsequently stored and shown as 1024 channel spectra on a display oscilloscope by the SBS 930 computer.

Eighteen states below 5 MeV excitation were observed to be populated in the decay of the $g_9/2$ ground state IAS. Most of the $P_{1/2}$ hole strength is used up in the 3.192, 3.469, and 3.702 MeV states which is in agreement with the $^{207}$Pb(d,p)$^{208}$Pb results. In Ref. 4 we make four spin assignments based on angular distributions for $(g_9/2,P_{3/2})_I$ configurations. Fig. 3.6-1 and Fig. 3.6-2 contain some of the angular distributions. In Ref. 4 we also discuss the possibility of interference between the resonance and background cross sections and ratios of on-resonance to off-resonance cross sections are quoted. We will neglect such discussion in the present report. Figure 3.6-3 gives the proton partial widths for the states observed in the decay of the $g_9/2$ analog resonance. In Sec. 3.8 a detailed examination of the $^4-(3.469$ MeV) state angular distribution is made and a wave function with relative signs for the $(g_9/2,P_{3/2})_I$ and $(g_9/2,P_{1/2})_I$ parentage coefficients is obtained.

The $^{207}$Pb(d,p)$^{208}$Pb experiment selects configurations(J,P)I, so that by using the $(2I+1)s_{dp}$ values and the $\Gamma_{P'}$ values, the inelastic partial width widths $\Gamma_{II/2J}$ can be deduced. In this discussion we assume the spin J states in $^{200}$Pb are pure single neutron states. In Table 3.6-1 we have compared these numbers, $\Gamma_{II/2J}$, with the $\Gamma_J$ values obtained in the present experiment. The $(p,p')$ widths should be greater than the (d,p) widths if configurations other than (J,P)I are significant, as for
Table 3.6-1. A Comparison of Widths from (p,p') and (d,p) Reactions

<table>
<thead>
<tr>
<th>Ex (MeV)</th>
<th>$\sum_j \Gamma_{1J} / \Gamma_{1}$</th>
<th>J</th>
<th>Ex (MeV)</th>
<th>$\Gamma_{11/2J}$</th>
<th>I</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.192</td>
<td>22.7 $^f$</td>
<td>$g_{9/2}$</td>
<td>3.19</td>
<td>26.6</td>
<td>5$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>3.469</td>
<td>23.8</td>
<td>$g_{9/2}$</td>
<td>3.47</td>
<td>23.3</td>
<td>4$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>3.702</td>
<td>7.9 $^g$</td>
<td>$g_{9/2}$</td>
<td>3.76</td>
<td>-</td>
<td>-</td>
<td>Pb</td>
</tr>
<tr>
<td>4.174</td>
<td>7.7 $^g$</td>
<td>$g_{9/2}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Pb</td>
</tr>
<tr>
<td>4.289</td>
<td>9.4 $^g$</td>
<td>$g_{9/2}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Pb</td>
</tr>
<tr>
<td>4.351</td>
<td>11.9</td>
<td>$g_{9/2}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Pb</td>
</tr>
<tr>
<td>4.475</td>
<td>14.9</td>
<td>$g_{9/2}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Pb</td>
</tr>
<tr>
<td>4.592</td>
<td>9.3 $^g$</td>
<td>$d_{5/2}$</td>
<td>4.70</td>
<td>7.1</td>
<td>3$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>4.967</td>
<td>13.8 $^f$</td>
<td>$d_{5/2}$</td>
<td>4.98</td>
<td>16.3</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.030</td>
<td>12.7</td>
<td>$d_{5/2}$</td>
<td>5.03</td>
<td>11.7</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.122</td>
<td>7.2 $^g$</td>
<td>$d_{5/2}$</td>
<td>5.12</td>
<td>6.2</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.238</td>
<td>7.0 $^g$</td>
<td>$d_{5/2}$</td>
<td>5.24</td>
<td>5.6</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.284</td>
<td>42.0 $^f$</td>
<td>$s_{1/2}$</td>
<td>5.28</td>
<td>50.0</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.769</td>
<td>1.0 $^g$</td>
<td>$d_{3/2}$</td>
<td>5.77</td>
<td>3.2</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.804</td>
<td>3.5 $^g$</td>
<td>$d_{3/2}$</td>
<td>5.80</td>
<td></td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.869</td>
<td>12.5 $^g$</td>
<td>$g_{7/2}$</td>
<td>5.85</td>
<td>10.6</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.914</td>
<td>9.5 $^g$</td>
<td>$d_{3/2}$</td>
<td>5.89</td>
<td>12.3</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.936</td>
<td>9.9 $^g$</td>
<td>$d_{3/2}$</td>
<td>5.93</td>
<td>9.6</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>5.958</td>
<td>24.8</td>
<td>$g_{7/2}$</td>
<td>5.96</td>
<td>23.4</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>6.000</td>
<td>(10.0)</td>
<td>$g_{7/2}$</td>
<td>6.00</td>
<td>5.7</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
<tr>
<td>6.078</td>
<td>4.0</td>
<td>$d_{3/2}$</td>
<td>6.05</td>
<td>4.5</td>
<td>1$^-$</td>
<td>Pb</td>
</tr>
</tbody>
</table>

- (d,p) results from Ref. 5.
- Excitation energies taken from Ref. 1.
- Inelastic width to state 1 at resonance J includes contributions from all possible neutron holes $j'$.
- Calculated from $((2I + 1) S_{11}^{\pi} \Gamma_{11/2J}/(2J + 1))$.
- Spins in parentheses tentatively assigned from present work.
- Excitation functions show some interference effects.
- Assigned from 208Pb(d,3n0), R. Ballini et al., Phys. Letters 26B, 215 (1968). See also Sec. 3.9.
example \((J,p^{-1})\). The widths should be equal when all such latter contributions are zero. Examination of the table shows that there is not a significant amount of mixing into the \(p_{1/2}\) neutron-hole configurations.

At least 15 states between 4.5 and 6.5 MeV were observed to be populated in the decay of the \(d_{5/2}\) (1.56 MeV) IAS. From a comparison with the \(^{207}_{207}\text{Ph}(d,p)\) results in Table 3.6-1, one can identify the four states at \(E_x = 4.69, 4.97, 5.03\) and 5.12 MeV as containing the configuration \((d_{5/2},p_{3/2})^{1}\) and therefore they have spin \(2^-\) or \(3^-\). A \(3^-\) spin assignment can be made for the 4.69 MeV state since this state is also observed at the \(g_{9/2}\) resonance and its integrated width is found to be 5.3 keV. The only \(i_{13/2}\) configuration with spin \(2^-\) or \(3^-\) and a width \(\Gamma < 5.3\) keV is the \((g_{9/2},p_{3/2})^{1}\) configuration. This configuration can give a \(3^-\) spin but not a \(2^-\) spin. Figure 3.6-3b gives only the larger proton partial widths for the \(d_{5/2}\) IAS.

Only six states (see Fig. 3.6-3c) were observed to be populated in the decay of the \(s_{1/2}\) IAS. The excitation functions for all six states showed resonances at other IAS energies. In particular the \(1^-\) state at 5.284 MeV is also excited weakly at the \(d_{5/2}\) resonance resulting in interference between the \(d_{5/2}\) and \(s_{1/2}\) resonances. Destructive interference at the backward angles may affect the widths in Table 3.6-1.

Thirty-one states were excited at the \(g_{7/2}(2.47\) MeV) or \(d_{3/2}(2.54\) MeV) IAS. Some of these states were not included in Figs. 3.6-3d and -3e because they could not be definitely assigned to the \(d_{3/2}\) or \(g_{7/2}\) resonance. All unassigned states are above 5.3 MeV. The only large unassigned state is at 5.730 MeV and its width would be 13.5 keV assuming a \(d_{3/2}\) configuration. The proton partial widths for the \(d_{3/2}\) IAS appear to be spread thinly over many states.

We hope in the near future to present a comparison between the observed widths, energies and spins of these \(^{208}_{208}\text{Pb}\) states with the theoretically calculated ones.

(F. Richard, P. von Brentano, W.G. Weitkamp, W. Wharton, and H. Wieman)

6 W.T. Pinkston and W.W. True, private communication.
3.7 Determination of the Total Widths of the Single Particle Analogue Resonances in $^{209}\text{Bi}$

Single particle analogue resonances in $^{209}\text{Bi}$ have been investigated in the elastic channel by several groups

\cite{1-3} and resonance parameters have been obtained. Since most of the resonances lie within a distance of $\Gamma$ to $2\Gamma$ of each other, the elastic scattering cross section shows a complicated interference pattern. Under these circumstances it is quite difficult to determine accurate total widths, whereas the parameter $(2J + 1)\Gamma_p/\Gamma$ may still be rather well determined. In the present study the total widths were determined from the inelastic channels which resonate strongly and selectively\cite{2-4} at various resonances.

Proton spectra from $^{208}\text{Pb(p,p')}$ for states in $^{208}\text{Pb}$ with an excitation energy up to 7 MeV using incident proton energies from 14-18 MeV were measured. Excitation functions were extracted and for each resonance a group of states, which resonated nearly exclusively at this resonance were considered and analyzed. An example of these states is shown in Fig. 3.7-1.

The analysis of these excitation functions presents a problem, however, as

![Excitation function for selected final states near each IAS in $^{209}\text{Bi}$](image)

Fig. 3.7-1. Excitation function for selected final states near each IAS in $^{209}\text{Bi}$. The solid curves are the best least squares fit.

3.469 MeV state at $90^\circ$ near $5/2^+$ resonance;
5.071 MeV " " $90^\circ$ " $3/2^-$ " $\frac{d\sigma}{d\Omega} \times 3$;
4.602 MeV " " $150^\circ$ " $5/2^-$ " $\frac{d\sigma}{d\Omega} \times 10$;
5.804 MeV " " $90^\circ$ " $d_5/2$ " $\frac{d\sigma}{d\Omega} \times 3$;
6.304 MeV " " $90^\circ$ " $s_1/2$ " $\frac{d\sigma}{d\Omega} \times 3$;
5.958 MeV " " $100^\circ$ " $d_3/2$ " $\frac{d\sigma}{d\Omega} \times 2$.

66
the resonances have a non-Lorentzian shape. We have overcome this problem by using a collision matrix consisting of a constant background term and a pole term. Such a collision matrix will lead to a cross section of the form.

\[ \sigma(\theta, E) = \sum_{\beta} |A_{\beta}(0)|^2 + \frac{b_{\beta}(6)}{(E - E_0) + i\Gamma/2} \]  

(1)

Here \( A_{\beta} \) and \( B_{\beta} \) are complex numbers which depend on the angle, while \( E_0 \) and \( \Gamma \) are real parameters. The sum is done over the spin channels \( \beta = (m_T, m_p, m'_T m'_p) \) of the reaction.

From Eq. (1) we immediately obtain a fit formula for the cross section

\[ \sigma(\theta, E) = \sigma_D + \frac{\sigma_0 \Gamma^2/4 + S(E - E_0)\Gamma/2}{(E - E_0)^2 + \Gamma^2/4} \]  

(2)

The meaning of the various parameters in Eq. (2) is clarified in Eq. (3).

\[ \sigma(\theta, \infty) = \sigma_D, \sigma(\theta, E_0 + \Gamma/2) - \sigma(\theta, E_0 - \Gamma/2) = S \]  

(3)

and \( \sigma(\theta, E_0) - \sigma_D = \sigma_0 \).

It should be emphasized that \( \sigma_0 \) is not the pure resonance cross section but contains contributions from interference terms. A few excitation functions showed a second much weaker resonance at a nearby energy (see Fig. 3.7-1). These excitation functions were fitted by allowing a second resonance term in Eq. (2), a procedure which includes the interference between the two resonances. Excitation functions to different final states but which resonated at the same resonance gave consistent values for \( \Gamma \) and \( E_0 \) to within the fitting errors. This is an important check on the validity of the Breit-Wigner formula for analog resonances, and shows that the parameters \( \Gamma \) and \( E_0 \) are indeed the total width and the resonance energy. These parameters obtained from a least squares analysis based on Eq. (2) are given in Table 3.7-1. An indication of the error in determining \( \Gamma \) is obtained by noting that the full width at half maximum, \( W \), of the cross section \( \{\sigma(\theta, E) - \sigma_D\} \) is closely related to:

\[ W = \Gamma(1 + 1/2(\frac{S}{\sigma_0})^2) + \text{terms of order } (\frac{S}{\sigma_0})^4. \]  

(4)

The formula shows that \( W \) and \( \Gamma \) are indeed nearly identical because in all cases studied we found \((S/\sigma_0)^2 < 0.1 \). The \( \Gamma \) extracted from the data depends critically on the proper value of \( \sigma_0/2 \) which further depends on knowing \( \sigma_D \) accurately. This emphasizes the advantage for fitting the resonances with Eq. (2).

In conclusion we have seen that a collision matrix consisting of a constant background amplitude and a Breit-Wigner term is describing the inelastic cross section rather well and that we can therefore extract reliable resonance
Table 3.7-1. $^{209}$Bi* Analogue Resonance Parameters

<table>
<thead>
<tr>
<th>IAS</th>
<th>$E_{\text{lab}}$ (MeV)$^{a,b}$</th>
<th>$\Gamma$(keV)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{9/2}$</td>
<td>14.918 $\pm$ 0.006</td>
<td>252 $\pm$ 10</td>
</tr>
<tr>
<td>$i_{11/2}$</td>
<td>15.715 $\pm$ 0.010</td>
<td>225 $\pm$ 20</td>
</tr>
<tr>
<td>$d_{15/2}$</td>
<td>16.336 $\pm$ 0.015</td>
<td>201 $\pm$ 30</td>
</tr>
<tr>
<td>$d_{5/2}$</td>
<td>16.496 $\pm$ 0.006</td>
<td>307 $\pm$ 10</td>
</tr>
<tr>
<td>$s_{1/2}$</td>
<td>16.966 $\pm$ 0.017</td>
<td>320 $\pm$ 20</td>
</tr>
<tr>
<td>$g_{7/2}$</td>
<td>17.428 $\pm$ 0.016</td>
<td>286 $\pm$ 25</td>
</tr>
<tr>
<td>$d_{3/2}$</td>
<td>17.475 $\pm$ 0.015</td>
<td>279 $\pm$ 20</td>
</tr>
</tbody>
</table>

a) The errors quoted in the Table are fitting errors, which are obtained from a $\chi^2$ fit, plus estimated systematic errors. Most of these values were obtained from a fit to several excitation functions.

b) The values for the resonance energy are based on a new energy calibration of the accelerator (Ref. 8).

parameters in this way.

(W.K. Dawson, C. Fred Moore, P. Richard, P. von Brentano, W. Wharton, and H. Wieman)

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Department of Physics, University of Texas, Austin, Texas.

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3.8 Configurations of the Lowest $4^-$ State in $^{208}$Pb

In this section we will give an analysis of the angular distribution of the resonant $^{208}$Pb($p,p'$)$^{208}$Pb going to the $4^-$ (3.469 MeV) state$^{1,2}$ (see also Sec. 3.6), and we will see that we can determine from such analysis not only the strength of various configurations contained in the $4^-$ state but also the relative signs of these configurations. We have chosen to analyze this particular case because rather careful measurements of this angular distribution$^1$ (Sec. 3.6)
have been made and also because the experiments showed that the cross section at
the top of the \( g_0/2 \) resonance at an incident proton energy of \( E_p = 14.9 \text{ MeV} \) is
nearly entirely due to the resonance\(^1\) (see Sec. 3.7). We can therefore neglect
the direct inelastic amplitudes, which simplifies the analysis very much.

A collision matrix which is appropriate for an isolated analog resonance \( J \) in proton scattering from channel \( c \) to \( c' \) has been given by Weidenmüller\(^3\) in
the form of Eq. (1).

\[
U_{cc'} = \frac{U_{cc'}}{U_{cc}} = \frac{i \frac{g_J}{g_{c c'}}}{(E - E_{c c'}) + i\Gamma/2}.
\tag{1}
\]

From this collision matrix we obtain a scattering amplitude and a cross section
for proton scattering on a spin 0 target in Eqs. (2) and (3).

\[
\mathcal{A}(I'M'\mu',\mu) = \mathcal{A}(I'M'\mu',\mu) + i \frac{1/2}{\kappa} \sum_{J} \frac{g_{J} g_{J'}}{E - E_{0} + i\Gamma/2} (2l + 1)^{1/2} \times \sum_{M'_{J} M_{J}} \left| \langle \ell' \mu' | M_{J} \rangle \langle \ell \mu | M'_{J} \rangle \right|^{2} \times \left| Y_{\ell' \mu'}(\vartheta',\varphi') \right|^{2}.
\tag{2}
\]

\[
\frac{d\sigma}{d\omega} = \frac{1}{2s + 1} \sum_{I'M'\mu'\mu} \left| \mathcal{A}(I'M'\mu'\mu) \right|^{2}.
\tag{3}
\]

In Eq. (2) the entrance and exit channels are characterized by the quantum num-
bers and coupling schemes \( 0(\ell s)j \) and \( I'(\ell' s')j' \) respectively. The orbital angu-
lar momenta \( \ell \) and \( \ell' \) are characterized uniquely by \( j \) and \( j' \) because of the parity
conservation. If we can assume that the partial widths \( g_{J}^{2} \) for the proton de-
cy of the analog resonance are entirely due to a partial neutron width relating
the parent analog state to the final state, then the partial amplitudes can be
factorized into a single particle amplitude \( g_{c c'}^{J} \mathcal{S} \mathcal{F} = g_{c c'}^{J} \mathcal{S} \mathcal{F} \exp(i\phi_{c c'}^{J} \mathcal{S} \mathcal{F}) \) and the
overlap integral

\[
C_{c c'}^{J} = \langle J_{M_{J}} T_{0} + \frac{1}{2}, T_{0} + \frac{1}{2} | (I' \mu')j' \rangle \langle J_{M'_{J}} T_{0} T_{0} \frac{1}{2}, \frac{1}{2} \rangle:
\]

\[
\frac{J}{g_{c c'}^{J}} = C_{c c'}^{J} g_{c c'}^{J} \mathcal{S} \mathcal{F}.
\tag{4}
\]

The overlap integral \( C_{I'I',J}^{J'I',J} \) can be calculated, if we know the wave function
of the final state and the parent analog state.

In our case we will assume the \( 9/2^+ \) ground state of \( ^{209}\text{Pb} \) to be a pure
single particle state and the \( 4^- (3.469 \text{ MeV}) \) state to be a combination of neutron
particle-hole configurations.
\[ |I'\rangle = \sum_{J_1'} a_{I_1J_1'}^J |(J_1'-1)J_1'\rangle. \]  
(5)

The \( a_{I_1J_1'}^J \) are real numbers because \( |I'\rangle \) is a bound state and therefore the \( C_{I_1J_1'}^J \) are also real numbers and have the values
\[ C_{I_1J_1'}^J = (-1)^{2J'+1} \cdot a_{I_1J_1'}^J \cdot \left( \frac{2I'+1}{2J'+1} \right)^{1/2}. \]  
(6)

Using Eqs. (2-6) and \( \bar{A} = 0 \), we find:
\[ \frac{d\sigma}{d\omega} = \sum_L A_L \rho_L = \frac{\lambda_J}{k^{1/2}} \sum_{I_1J_1'} f(LJ, J') |\rho^6_{J_1'} | \left( \begin{array}{c} g_{J_1'}^q \end{array} \right) \left( \begin{array}{c} g_{J_1}^q \end{array} \right) \]
\[ \times e^{i(\phi_{J_1'}^q - \phi_{J_1}^q)} \left( \begin{array}{c} a_{I_1J_1'}^J \\ a_{I_1J_1'}^{J'} \end{array} \right), \]  
(7)

where \( f \) is a purely geometrical function, which depends only on the spins and has been evaluated from Eqs. (2) and (3) by a computer program. Equation (7) agrees with an expression provided by D. Rohon.\(^4\)

The complex single particle amplitudes \( S_{I_1J_1'}^{SP}(E_{p'}) \) depend primarily on the angular momentum \( J' \) and the energy \( E_{p'} \) of the emitted proton. These can be calculated from the Lane model, however calculations have shown that for our case Coulomb phases and Coulomb penetrabilities with \( R = 0.3 \) fm give phase differences and energy dependence of widths which are approximately equal to those of the Lane model.\(^3\) We have used the single particle widths \( T_{SP} = |S_{I_1J_1'}^{SP}|^2 \) measured in the decay of the \( 0^+ \) \( 208\text{Bi} \) g.s. analog resonance\(^5\) with a correction for the energy dependence. At \( E_{p'} = 11.4 \) MeV:
\[ \Gamma_{1/2}^{SP} = 27 \text{ keV}, \Gamma_{5/2}^{SP} = 5.80 \text{ keV}, \Gamma_{3/2}^{SP} = 22.2 \text{ keV}. \]
\[ \Gamma_{7/2}^{SP}, \Gamma_{9/2}^{SP}, \text{etc.}, \]
will be neglected.

With these three configurations Eq. (5) becomes:
\[ |4\rangle = a_1^{J'} |(p_{1/2} g_{9/2})^4\rangle + a_3^{J'} |(p_{3/2} g_{9/2})^4\rangle + a_5^{J'} |(f_{5/2} g_{9/2})^4\rangle \]  
(8)

where \( a_{I_1J_1'}^{J'} \) is denoted by \( a_{(J_1', \times J_1')}. \) The limitation seems to be not unreasonable since we expect the spectroscopic factors of the other particle-hole configurations such as \( (h_{9/2}^2 g_{9/2}) \) to be small due to the large energy difference between the unperturbed configurations and the \( 4^- (3.459 \text{ MeV}) \) state. Furthermore, the strength \( a_1 \) of the \( (p_{1/2} g_{9/2}) \) configuration is rather well known from the \( 207\text{Pb}(d,p) \) reaction\(^7\) and is \( |a_1|^2 = 0.97 \pm 0.05. \)

If we use these remarks and Eqs. (7) and (8) and the values of \( A_L \), which were obtained from a fit to the experimental data in Ref. 1, we obtain the
following set of numerical equations:

\[ A_2/A_0 = -0.36 \pm 0.01 = 1.496a_1a_1 - 0.257a_3^2 + 0.292a_1a_5 - 0.114a_3a_5 - 0.57a_5^2 \]  \((9a)\)

\[ A_4/A_0 = -0.03 \pm 0.04 = 0.308a_3a_5 - 0.026a_5^2 \]  \((9b)\)

\[ a_1 \geq 0.92 \]  \((9c)\)

\[ 0.9(27a_1^2 + 22.5a_3^2 + 5.85a_5^2) = 23.8 \]  \((9d)\)

\[ a_1^2 + a_3^2 + a_5^2 \leq 1. \]  \((9e)\)

An arbitrary overall sign in the wave function is fixed by Eq. \((9c)\) and the normalization of the wave function is considered in \((9e)\). These equations have the solution

\[ a_1 = +0.96 \pm 0.02, \ a_3 = -0.26 \pm 0.03, \ a_5 = +0.07 \pm 0.15. \]  \((10)\)

From the structure of the Eqs. \((9)\) it is evident that the value of \(a_5\) depends very sensitively on the value of \(A_4/A_0\), and we obtain only a weak estimate for \(a_5\). At the same time, however, the value of \(a_3\) depends only weakly on the values and errors of \(A_0/A_0\) and \(A_4/A_0\), and thus the magnitude and sign of \(a_3\) are determined quite reliably. Shell model calculations for the particle-hole structure of \(^{208}\text{Pb}\) have given for the lowest \(4^-\) state the values

\[ a_1 = +0.980, \ a_3 = -0.121, \text{and} \ a_5 = -0.07 \]  \((11)\)

as calculated by Brown and Kuo\(^8\) and the values

\[ a_1 = +0.962, \ a_3 = -0.163, \text{and} \ a_5 = -0.21 \]  \((12)\)

as calculated by Pinkston and True.\(^9\) The complete wave function of the \(4^-\) state may contain more configurations than given in Eqs. \((9)\) and \((10)\). However, the \(4^-\) state is not excited in the decay of the higher neutron single particle analog resonances,\(^1,2\) which rules out many neutron particle-hole configurations; it is also not excited appreciably in the \(^{209}\text{Bi}(t,a)^{208}\text{Pb}\) reaction,\(^10\) which rules out many proton particle-hole configurations.

(J. Bondorf, P. Richard, and P. von Brentano)

\[ \text{References:} \quad 1 \text{ P. Richard, W.C. Weitkamp, W. Wharton, H. Wieman, and P. von Brentano, Phys. Letters 58, B (1967), and to be published.} \]
\[ 2 \text{ S.A.A. Zaidi, J.L. Parish, J.C. Kulleck, C. Fred Moore, and P. von Brentano, Phys. Rev. 166, 1312 (1968).} \]
\[ 3 \text{ H.A. Weidenmüller, Nucl. Phys. A69, 289 (1967).} \]
\[ 4 \text{ D. Robson, private communication.} \]
\[ 6 \text{ B.L. Anderson, J.F. Bondorf, and B.S. Madesn, Phys. Letters 22, 651 (1966).} \]
3.9  \( _1^- \) Neutron Particle-Hole States in \( ^{208}_{\text{Pb}} \) Populated by Proton Decay of Analogue Resonances

An isobaric analogue resonance formed by the proton bombardment of an even closed neutron-shell nucleus may be considered as a superposition of a single-particle state and a set of two-particle-one-hole states. If the resonance decays through the inelastic proton channel, a neutron particle-hole state is formed,\(^1\)\(^-\) and since the particle and the hole lie in different major shells, this usually results in negative-parity states. The formation of such states by analogue resonances has been found to be strong and selective.\(^4\)

The neutron particle-hole states formed in this way are usually bound and will decay by gamma-ray transitions to lower-lying states. Because of the usual spin-parity selection rules,\(^5\) states of angular momentum greater than one are most likely to cascade through lower-lying \( 2^+ \) and \( 3^- \) states. However, \( 1^- \) neutron particle-hole states are strongly favored to make E1 ground-state transitions.\(^6\)

Thus, \( 1^- \) neutron particle-hole states may be identified by exciting them through \((p,p')\) reactions on an analogue resonance and observing their ground-state gamma-ray decays. We have previously identified \( 1^- \) states in \( ^{140}_{\text{Ce}} \) by this method, using \( p-\gamma \) coincidences,\(^7\) and a similar coincidence method has been employed in \((d,p)\) reactions.\(^7\) If the gamma rays are detected with good resolution, no proton coincidence is required since the resonant behavior and relatively large transition energies identify the states of interest. This procedure, which was used in the present work, has several experimental advantages: one can take advantage of the good resolution now available with \( \text{Ge(Li)} \) gamma-ray detectors, and, because of the large widths of the analogue resonances (\( \sim 250 \) keV), one can use fairly thick targets, thereby reducing effects due to surface contaminants. (In fact, accelerators with poor beam energy resolution could be used very effectively in these experiments.)

The angular momentum relations in a reaction of this type are particularly simple, and greatly simplify the interpretation of gamma-ray angular distributions. In particular: (a) the total angular momentum carried in by the incident proton is determined by the spin of the analogue resonance, i.e., by the bombarding energy. (b) The total angular momentum of the neutron particle of the particle-hole state is equal to the spin of the analogue resonance. (c) The total angular momentum carried away by the outgoing proton is characteristic of the neutron hole and is unique if the particle-hole state has a single hole configuration. (d) Since the outgoing proton is unobserved, the contributions of different neutron hole configurations to the gamma-ray angular distribution will add incoherently. (e) In the case of overlapping resonances, e.g., \( g7/2 \) and \( d3/2 \), the different particle configurations will interfere in the gamma-ray angular
distribution only when they have the same hole configuration. Gamma-ray angular distributions have been calculated for the relevant particle and hole configurations in 208Pb assuming 1\textsuperscript{−} or 2\textsuperscript{−} particle-hole states. These angular distributions are given in Table 3.9-1.

Table 3.9-1. Calculated Gamma-Ray Angular Distributions for Ground-State Transitions from Neutron Particle-Hole States

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Spin and Parity of Particle-Hole State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>Hole</td>
</tr>
<tr>
<td>d\textsubscript{5/2}</td>
<td>P\textsubscript{1/2}</td>
</tr>
<tr>
<td>f\textsubscript{5/2}</td>
<td>P\textsubscript{3/2}</td>
</tr>
<tr>
<td>d\textsubscript{5/2}</td>
<td>P\textsubscript{3/2}</td>
</tr>
<tr>
<td>s\textsubscript{1/2}</td>
<td>P\textsubscript{1/2}</td>
</tr>
<tr>
<td>s\textsubscript{1/2}</td>
<td>f\textsubscript{5/2}</td>
</tr>
<tr>
<td>s\textsubscript{1/2}</td>
<td>P\textsubscript{3/2}</td>
</tr>
<tr>
<td>g\textsubscript{7/2}</td>
<td>f\textsubscript{5/2}</td>
</tr>
<tr>
<td>g\textsubscript{7/2}</td>
<td>P\textsubscript{3/2}</td>
</tr>
<tr>
<td>d\textsubscript{3/2}</td>
<td>P\textsubscript{1/2}</td>
</tr>
<tr>
<td>d\textsubscript{3/2}</td>
<td>f\textsubscript{5/2}</td>
</tr>
<tr>
<td>d\textsubscript{3/2}</td>
<td>P\textsubscript{3/2}</td>
</tr>
</tbody>
</table>

In the present work we have used the approach outlined above to study the gamma-ray decay of high-lying neutron particle-hole states in 208Pb populated by inelastic proton scattering on the g\textsubscript{9/2} (14.92 MeV), d\textsubscript{5/2} (15.72 MeV), s\textsubscript{1/2} (16.48 MeV), and d\textsubscript{3/2} (17.47 MeV) analogue resonances in 209Bi. The reaction is shown schematically in Fig. 3.9-1. A 20.7 cm\textsuperscript{3} coaxial Ge(Li) detector having an energy resolution of about 15 keV for the gamma rays of interest (5-8 MeV) was placed about 15 cm from the 208Pb target. The target was bombarded with protons from the University of Washington 3-stage FN Tandem Accelerator, and gamma-ray spectra were recorded with an on-line computer. Figure 3.9-2 shows a portion of the gamma-ray spectra measured on the d\textsubscript{5/2}, s\textsubscript{1/2}, and d\textsubscript{3/2} resonances. Five prominent peaks (labeled h, c, e, g, and 160\textsubscript{6,13}) and a number of weaker ones are visible in these spectra. The strongest peak is due to oxygen contamination in the target and comes from the ground-state decay of the 3\textsuperscript{−} (6.131 MeV) states in 160. This peak together with one from the 3\textsuperscript{−} (2.609 MeV) state in 208Pb was used for energy calibration. Table 3.9-2 summarizes the analysis of peaks found in
3.9 1− Neutron Particle-Hole States in 208\(^{\text{Pb}}\) Populated by Proton Decay of Analogue Resonances

An isobaric analogue resonance formed by the proton bombardment of an even closed neutron-shell nucleus may be considered as a superposition of a single-particle state and a set of two-particle-one-hole states. If the resonance decays through the inelastic proton channel, a neutron particle-hole state is formed,\(^1\)−\(^3\) and since the particle and the hole lie in different major shells, this usually results in negative-parity states. The formation of such states by analogue resonances has been found to be strong and selective.\(^4\)

The neutron particle-hole states formed in this way are usually bound and will decay by gamma-ray transitions to lower-lying states. Because of the usual spin-parity selection rules,\(^5\) states of angular momentum greater than one are most likely to cascade through lower-lying 2\(^+\) and 3\(^+\) states. However, 1− neutron particle-hole states are strongly favored to make E\(_1\) ground-state transitions.\(^6\)

Thus, 1− neutron particle-hole states may be identified by exciting them through (p,p') reactions on an analogue resonance and observing their ground-state gamma-ray decays. We have previously identified 1− states in 140\(^{\text{Ce}}\) by this method, using p-\(\gamma\) coincidences.\(^5\) and a similar coincidence method has been employed in (d,p) reactions.\(^7\) If the gamma rays are detected with good resolution, no proton coincidence is required since the resonant behavior and relatively large transition energies identify the states of interest. This procedure, which was used in the present work, has several experimental advantages: one can take advantage of the good resolution now available with Ge(Li) gamma-ray detectors, and, because of the large widths of the analogue resonances (~250 keV), one can use fairly thick targets, thereby reducing effects due to surface contaminants. (In fact, accelerators with poor beam energy resolution could be used very effectively in these experiments.)

The angular momentum relations in a reaction of this type are particularly simple, and greatly simplify the interpretation of gamma-ray angular distributions. In particular: (a) the total angular momentum carried in by the incident proton is determined by the spin of the analogue resonance, i.e., by the bombarding energy. (b) The total angular momentum of the neutron particle of the particle-hole state is equal to the spin of the analogue resonance. (c) The total angular momentum carried away by the outgoing proton is characteristic of the neutron hole and is unique if the particle-hole state has a single hole configuration. (d) Since the outgoing proton is unobserved, the contributions of different neutron hole configurations to the gamma-ray angular distribution will add incoherently. (e) In the case of overlapping resonances, e.g., \(g7/2\) and \(d3/2\), the different particle configurations will interfere in the gamma-ray angular
distribution only when they have the same hole configuration. Gamma-ray angular distributions have been calculated for the relevant particle and hole configurations in $^{208}$Pb assuming $1^-$ or $2^-$ particle-hole states. These angular distributions are given in Table 3.9-1.

Table 3.9-1. Calculated Gamma-Ray Angular Distributions for Ground-State Transitions from Neutron Particle-Hole States

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Hole</th>
<th>Spin and Parity of Particle-Hole State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{5/2}$</td>
<td>$F_{1/2}$</td>
<td>$1 + \frac{10}{49} P_2 - \frac{18}{49} P_4$</td>
</tr>
<tr>
<td>$d_{5/2}$</td>
<td>$f_{5/2}$</td>
<td>$1 - \frac{2}{35} P_2$</td>
</tr>
<tr>
<td>$d_{5/2}$</td>
<td>$F_{3/2}$</td>
<td>$1 + \frac{10}{49} P_2 + \frac{32}{49} P_4$</td>
</tr>
<tr>
<td>$s_{1/2}$</td>
<td>$F_{1/2}$</td>
<td>$1 - \frac{5}{14} P_2$</td>
</tr>
<tr>
<td>$s_{1/2}$</td>
<td>$f_{5/2}$</td>
<td>$1 + \frac{25}{294} P_2 + \frac{32}{49} P_4$</td>
</tr>
<tr>
<td>$s_{1/2}$</td>
<td>$F_{3/2}$</td>
<td>$1 + \frac{1}{2} P_2$</td>
</tr>
<tr>
<td>$s_{1/2}$</td>
<td>$P_{1/2}$</td>
<td>$1 - \frac{5}{14} P_2$</td>
</tr>
<tr>
<td>$g_{7/2}$</td>
<td>$f_{5/2}$</td>
<td>$1 - \frac{10}{49} P_2$</td>
</tr>
<tr>
<td>$g_{7/2}$</td>
<td>$P_{3/2}$</td>
<td>$1 + \frac{25}{294} P_2 - \frac{18}{49} P_4$</td>
</tr>
<tr>
<td>$d_{3/2}$</td>
<td>$P_{1/2}$</td>
<td>$1 + \frac{1}{2} P_2$</td>
</tr>
<tr>
<td>$d_{3/2}$</td>
<td>$f_{5/2}$</td>
<td>$1 + \frac{2}{5} P_2$</td>
</tr>
<tr>
<td>$d_{3/2}$</td>
<td>$P_{3/2}$</td>
<td>$1 - \frac{5}{14} P_2$</td>
</tr>
</tbody>
</table>

In the present work we have used the approach outlined above to study the gamma-ray decay of high-lying neutron particle-hole states in $^{208}$Pb populated by inelastic proton scattering on the $g_{9/2}$ (14.92 MeV), $d_{5/2}$ (15.72 MeV), $s_{1/2}$ (16.43 MeV), and $d_{3/2}$ (17.47 MeV) analogue resonances in $^{208}$Bi. The reaction is shown schematically in Fig. 3.9-1. A 20.7 cm$^3$ coaxial Ge(Li) detector having an energy resolution of about 15 keV for the gamma rays of interest (5-8 MeV) was placed about 15 cm from the $^{208}$Pb target. The target was bombarded with protons from the University of Washington 3-stage FN Tandem Accelerator, and gamma-ray spectra were recorded with an on-line computer. Figure 3.9-2 shows a portion of the gamma-ray spectra measured on the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ resonances. Five prominent peaks (labeled b, c, e, f, and g, and $^{150}$O$_{6,13}$) and a number of weaker ones are visible in these spectra. The strongest peak is due to oxygen contamination in the target and comes from the ground-state decay of the $3^-$ (6.131 MeV) states in $^{150}$O. This peak together with one from the $3^-$ (2.509 MeV) state in $^{208}$Pb was used for energy calibration. Table 3.9-2 summarizes the analysis of peaks found in


<table>
<thead>
<tr>
<th>Peak Label</th>
<th>$\gamma$-Ray Energy (MeV)</th>
<th>Relative Transition Strength</th>
<th>G.S. Branching Fraction</th>
<th>Angular Dist. Coeff.</th>
<th>Comparison with other Data</th>
<th>Assigned $J^\pi$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>5.08</td>
<td>0.08 0.08 0.15</td>
<td>67 ± 12 0.46 ± 0.52</td>
<td>5.071 --- ---</td>
<td>(1) 1^-</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>5.27</td>
<td>0.26 1.00 0.27</td>
<td>80 ± 8 -0.10 ± 0.38</td>
<td>5.284 5.28 5.52</td>
<td>1^-</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>5.50</td>
<td>0.46 0.57 0.33</td>
<td>78 ± 7 -0.64 ± 0.35</td>
<td>5.505 5.52 5.679</td>
<td>1^-</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>5.63</td>
<td>0.15 --- ---</td>
<td>45 ± 20 ---</td>
<td>5.679 --- ---</td>
<td>(1,2)^-</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>5.94</td>
<td>0.10 --- ---</td>
<td>60 ± 2 -0.41 ± 0.16</td>
<td>5.936 5.93 6.255 (6.25)</td>
<td>1^-</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>6.27</td>
<td>0.14 0.13 0.14</td>
<td>45 ± 5 -1.13 ± 0.36</td>
<td>6.255 6.304 6.400</td>
<td>1^-</td>
<td>(5)</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>6.32</td>
<td>0.12 0.45 0.12</td>
<td>73 ± 12 -0.02 ± 0.49</td>
<td>6.304 --- ---</td>
<td>1^-</td>
<td>(6)</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>6.49</td>
<td>0.07 0.07 0.11</td>
<td>60 ± 8 0.21 ± 0.40</td>
<td>6.400 --- ---</td>
<td>1^-</td>
<td>(7)</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>6.73</td>
<td>--- --- ---</td>
<td>6.7 ± 3 0.14 ± 0.47</td>
<td>6.730 6.72 7.072 (7.05)</td>
<td>1^-</td>
<td>(8)</td>
<td></td>
</tr>
<tr>
<td>j</td>
<td>7.08</td>
<td>0.11 0.09 0.12</td>
<td>50 ± 4 0.21 ± 0.25</td>
<td>7.072 7.05 7.32 (1^-)</td>
<td>1^-</td>
<td>(9)</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>7.38</td>
<td>0.04 0.07 0.06</td>
<td>--- 0.52 ± 0.47</td>
<td>7.32 7.65 7.65 (7.65)</td>
<td>1^-</td>
<td>(10)</td>
<td></td>
</tr>
<tr>
<td>l</td>
<td>7.65</td>
<td>0.02 0.05 0.04</td>
<td>--- 0.93 ± 0.52</td>
<td>--- ---</td>
<td>---</td>
<td>(11)</td>
<td></td>
</tr>
</tbody>
</table>

Comments:

(1) $(p,p')$ state at 5.071 resonates on $i_{11/2}$ analogue resonance. (see text)
(2) $(p,p')$ state at 5.505 shows considerable non-resonant strength. (see text)
(3) $(p,p')$ state at 5.679 was selected over state at 5.646 because the former resonates only on the $d_{5/2}$ res.
(4) Parentheses around energies in $(\gamma,\gamma)$ column indicate states not established to be from $^{208}$Pb in Ref.10.
(5) Plate gap in $(p,p')$ data on $d_{3/2}$ resonance.
(6) Branching fraction is 1/10 of other states observed. (see text)
(7) Excitation energy of this state is about 300 keV above neutron binding energy in $^{208}$Pb. (see text)
these spectra. The criteria for inclusion of a peak in this table were: (a) the peak must be apparent in at least two independent experimental runs, (b) the peak must show resonant behavior, and (c) the peak must correspond closely in energy and in resonant behavior to a state observed in \((p,p')\) measurements, if such data is available.

On the \(d_3/2\) resonance, which populates most of the states observed, measurements were made at 55°, 90°, 110°, and 125° to obtain crude angular distributions of the gamma rays. These points were fitted with a distribution of the form \(W(\theta) = a_0(1 + a_2(\cos \theta))\) and the coefficients \(a_0\) and \(a_2\) were evaluated.

Table 3.9-2 summarizes the results of these measurements. The energies, branching fractions, and \(a_2\) coefficients of the observed peaks are given. The branching fractions were calculated using the extracted coefficient \(a_0\) (except in the case of peak (d) where it was not available) and the 90° cross section obtained from Ref. 4. This procedure neglects the effects of the inelastic proton angular distribution. However, recent measurements of some of the angular distributions all indicate that the relative error thereby incurred is less than 10%. There is also an absolute error of about 20% on the branching fraction normalization due to the uncertainty in the detection efficiency of the Ge(Li) detector.

Table 3.9-2 also lists the energies of states observed in \((p,p')\), \((d,p)\) and resonant gamma-ray absorption \((\gamma,\gamma)\) reaction measurements which we have associated with the states observed in the present work. The \((d,p)\) reaction would be expected to select only states with \(p_{1/2}\)-hole configurations, and both of the states observed in that reaction have been found to have strong ground state transitions and are seen in Table 3.9-2 to have negative \(a_2\)-values, which is consistent, according to Table 3.9-1, with a \((d_3/2,p^-1)\) configuration. The \((\gamma,\gamma)\) reaction populates spin 1 states via \(E1\) or \(M1\) transitions. The states given in this column in parentheses are known to come from lead but not necessarily from \(^{208}\)Pb. Since the particle-hole states we expect to populate have the particle and the hole in different major shells, they are likely to be negative parity.

There is a possibility that a high-lying \(2^-\) neutron particle-hole state can have an observable \(N2\) ground-state branch if its reduced nuclear matrix elements with lower-lying collective states are small. Such a branch has been observed in \(^{16}O\). However, the ratio of the Weisskopf widths in \(^{208}\)Pb for neutron single-particle transitions from a \(2^-\) state at 6.3 MeV to the ground state and the \(3^-\) (2.609 MeV) state is only \(R(N2)/R(M1) = 6 \times 10^{-4}.\)
Fig. 3.9-2. The figure shows the high-energy portion of the gamma-ray spectra observed with a 20.7 cm$^3$ Ge(Li) detector at proton bombarding energies corresponding to analogue resonances in $^{209}$Bi. The peaks labeled a-k are identified as second-escape peaks from ground-state transitions in $^{208}$Pb.

In Table 3.9-2 we have assigned $J^M = 1^-$ in those cases where there is a large ground state branching fraction, a definitely negative $a_2$, or a state also definitely observed in resonant gamma absorption. In several cases the data bears further comments, which will be given here. State (a): Although this state has a sizable g.s. branch it has been observed in (p,p$'$) to resonate on the $^11/2^+$ resonance. The latter behavior is unlikely for a $1^-$ state. Thus the state is either an unresolved doublet or the association of this gamma ray with the 5.071 (p,p$'$) state is incorrect. State (c): This state has considerable non-resonant strength in (p,p$'$) and is presumably collective. Therefore the angular distribution considerations given above do not apply to this state. State (i): This state has a small g.s. branch and was only observed because it was strong in (p,p$'$). This suggests that the g.s. branch is inhibited for reasons of structure or spin or that the (p,p$'$) state is an unresolved doublet. State (i): The excitation energy of this state is about 300 keV above the neutron binding energy.
in $^{208}$Pb, and thus there is some question as to whether it could come from $^{208}$Pb. It is apparently at the proper energy to arise from the first escape peak of the 7.115 MeV gamma ray from $^{160}$O. However, this is unlikely because the expected second escape peak is not present in sufficient strength.

The present work could be substantially improved by using a Ge(Li) detector with better resolution. More careful angular distributions could provide specific information about the hole-configurations of the states. In addition, it should be possible to apply the technique to a wide variety of nuclei.


3.10 Electric Dipole Transition from the $2f_{7/2}$ Isobaric Analogue Resonance

to the $2d_{5/2}$ Ground State in $^{141}$Pr

A measurement of electric dipole gamma rays from isobaric analog states (IAS) in heavy nuclei is interesting since it provides information on the IAS and the low-lying states$^{1-4}$ as well as the matrix elements, $\langle F \rangle$, for the $E1$ gamma decay, and for the analogous first forbidden beta decay$^{1-3}$ (Fig. 3.10-1). Since the IAS in heavy nuclei are located in the high excitation energy region, they decay mainly by particle emission, so that the electromagnetic radiation branches are very small. $E1$ gamma transitions from IAS in medium nuclei with $N = 50$ have been measured with a large NaI crystal.$^5$ However for heavy nuclei with closely
spaced low-lying levels, well isolated high energy gamma rays from the IAS to such low-lying states may be observed by use of good resolution Ce(Li) crystals despite an extremely small detection efficiency.

We measured the El gamma rays from the $2f_{7/2}$ IAS to the $2d_{5/2}$ ground state in $^{141}$Pr(N = 82), (which corresponds to the first forbidden beta decay $^{141}$Ce $\rightarrow$ $^{141}$Pr). The $2f_{7/2}$ resonance analog to the ground state of $^{141}$Ce, was excited by the proton capture reaction on $^{140}$Ce at $E_p = 9.75$ MeV. Proton beams of 0.6 - 1.0 μA were provided by the University of Washington FN tandem accelerator. The target used was a self-supporting natural Ce (88.43% of $^{140}$Ce) with a thickness of 0.91 mg/cm². This thickness was obtained from the Rutherford scattering yield of 5 MeV protons at 35°. The gamma ray detector was a 20.7 cm³ Ce(Li) crystal. In order to attenuate low energy gamma rays and neutrons, an absorber of 103 mm thick paraffin containing 15% Li₂CO₃, followed by a 9.6 mm thick PbSn alloy was inserted between the target and the detector. An absolute detector efficiency was obtained by observing the $^{12}$C(p,p') reaction, which is very close to the gamma ray energy of present interest.

The $2f_{7/2}$ isobaric analog resonance was measured in an excitation function of the $^{140}$Ce(p,p') reaction. Gamma ray spectra were subsequently observed at several proton energies on- and off-resonance at 90° and 125° to the beam. Apart from gamma rays due to (p,p') reactions on oxygen contaminants, we found clearly a single isolated resonant line of 14.95 ± 0.05 MeV at $E_p = 9.758$ MeV (Fig. 3.10-2). This line is the El gammaray transition from the $2f_{7/2}$ IAS to the ground state ($2d_{5/2}$) in $^{141}$Pr. The anisotropy of this line, after subtraction of the off-resonance contributions, was found to be $Y(90°)/Y(125°) = 1.29$ (+ 2%). This value also supports the assignment of the gamma rays to the transition $f_{7/2} - d_{5/2}$ in view of the calculated anisotropies $Y(90°)/Y(125°)$ = 1.18 and 0.763 for transitions from IAS ($2f_{7/2}$) to the ground ($2d_{5/2}$) state and to the 14.5 keV first excited ($1g_{7/2}$) state respectively.

The gamma transition width $\Gamma_{\gamma 0}$ was obtained from the on-resonance gamma ray yield corrected for the off-resonance contribution. Assuming little effects
Fig. 3.10-2. (a) Energy spectrum of gamma rays at \( E_p = 9.768 \text{ MeV} \) 2f\( \frac{7}{2} \) resonance in \(^{140}\text{Pr}\). The 2 escape and 1 escape peaks are labeled \( E_2 \) and \( E_1 \), respectively. (b) Expanded energy spectra of the ground state transition \((\gamma_0)\) at \( E_p = 9.768 \text{ MeV} \) (2f\( \frac{7}{2} \) resonance) and at \( E_p = 10.087 \text{ MeV} \) (off resonance). This plot was obtained by summing up counts of nearest three channels.

of interference with non-resonant contributions to the IAS resonance cross section, we used the single resonance formula,

\[
\frac{d\sigma(p, \gamma_0)}{d\Omega} = \frac{\Gamma_p \Gamma_0 (1 + A_s \cos \theta)}{4 \pi (2s + 1)(2I + 1)} \frac{(E_p - E_0)^2 + (\Gamma/2)^2}{(E_p - E_0)^2 + (\Gamma/2)^2} \tag{1}
\]

where the resonance parameters are \( \Gamma_p = 12 \text{ keV}, \Gamma = 61 \text{ keV}, \) \( J = 7/2, s = 1/2, \) and \( I = 0 \). The transition probability obtained is

\[
\Gamma_{\gamma_0} (\exp) = 24 \pm 10 \text{eV} \quad \left( \Gamma_{\gamma_0} = 2.7 \pm 1.0 \cdot 10^{-17} \text{sec} \right). \tag{2}
\]

The matrix element of the El transition from the IAS,

\[
\frac{1}{\sqrt{2 \Gamma_0}} T_ j | i \rangle,
\]

is estimated by using the \( j-j \) coupling single particle wave functions with pure \( T \) spins, \( | f \rangle_0 \) and \( | i \rangle_0 \), as follows.
\[ 0 \left\langle \xi \left| m_{\gamma} \right| \text{IAS} \right\rangle_0 = 0 \left\langle \xi \left| m_{\gamma} \right| \frac{T_0}{\sqrt{2T_0}} \right\rangle_0 = \frac{1}{\sqrt{2T_0}} \left\langle \xi \left| [m_{\gamma}, T_-] \right| \frac{1}{\sqrt{2T_0}} \right\rangle_0 = \frac{1}{\sqrt{2T_0}} M_{SP} (3) \]

where

\[ s_{m_{\gamma}} = \sum_{\lambda} \left\{ \left( 1 - \frac{2}{\lambda} \right) a_{\lambda}^\dagger a_{\lambda} - \left( \frac{2}{\lambda} \right) b_{\lambda}^\dagger b_{\lambda} \right\}, T_- = \sum_{\delta} a_{\delta}^\dagger b_{\delta}^\dagger \text{ and } [m_{\gamma}, T_-] = \sum_{\lambda} a_{\lambda}^\dagger b_{\lambda}. \]

The \( a_{\lambda}^\dagger (b_{\lambda}^\dagger) \) and \( a_{\lambda} (b_{\lambda}) \) are creation and annihilation operators for proton (neutron). It is interesting to note that the main El transition from \( T_-|1\rangle \) is due to a coherent sum of a proton transition amplitude \( (2f_7/2)_p \rightarrow (2d_5/2)_p \) with effective charge \( e_{eff} = (1 - (Z/A))a \) and a neutron one \( (2f_7/2)_n \rightarrow (2d_5/2)_n \) with \( e_{eff} = - (Z/A)a \). They sum up with opposite signs, resulting in a single particle transition matrix \( M_{SP} \) with \( e_{eff} = e \), as shown in Eq. (3).

The ratios of the observed El matrix element \( |M|_{EXP} = \left\langle \xi \left| m_{\gamma} \right| \text{IAS} \right\rangle_{EXP} \) to the matrix element \( |M|_{SP}/\sqrt{2T_0} \) estimated using j−j coupling single particle wave functions\(^5\) with pure \( \Gamma \) spin is obtained as

\[ \frac{2T_0 |M|_{SP}^2}{|M|_{EXP}^2} = \frac{2T_0 \Gamma_{\gamma}(EXP)}{\Gamma_{\gamma}(SP)} = 0.075 \pm 0.03. \]

The experimental \( |M|^2 \) is hindered by a factor 13 with respect to the single particle estimate \( |M|_{SP}^2/2T_0 \). A part of the hindrance factor, \( F_{C} \approx 4 \), may be attributed to the effect of collective states\(^6\) and a factor \( F_{p} = (U^{2}_{2}(2f_7/2)U^{*}_{2}(2d_5/2))^{-1} \approx 1.3 \), to the effect of pairing correlations.\(^10\) Quite recently a similar order of hindrance has been found in El transitions from IAS in the medium nucleus \( 89Y.\)^5

The first forbidden transition operator is expressed on the basis of \( \xi \) approximation\(^15\) as

\[ - C_{\nu} \xi_{\nu} m_{\beta}^\dagger = - C_{\nu} \xi_{\nu} m_{\beta}^\dagger (\Lambda - 1.2 \Lambda_{1} - 1) \]

where \( m_{\beta} = \int_{x} \xi_{\nu} \), \( \Lambda = - i \int_{x} / \xi_{\nu} \), \( \Lambda_{1} = i \int_{x} / \xi_{\nu} \), and \( \xi = a_{\gamma}/2R \). Assuming \( T_+ \left| f \right\rangle \approx 0 \), we can relate the \( m_{\beta} \) matrix to the analogous gamma one \( m_{\gamma}^\dagger \) as

\[ \left\langle f | m_{\beta}^\dagger \right\rangle = \left\langle f | m_{\gamma}^\dagger, T_- \right\rangle \frac{\Gamma_{\gamma}}{\sqrt{2T_0}} \left\langle f | m_{\gamma} \right| \text{IAS} \right\rangle. \]

By using \( \sqrt{2T_0} \left\langle f | m_{\gamma} \right| \text{IAS} \right\rangle_{EXP} \) for the \( m_{\beta} \) matrix element and the experimental \( |M_{\beta}| \) obtained from the beta decay probability,\(^11\) we get from Eq. (5)

\[ (\Lambda - 1.2 \Lambda_{1} - 1)^2 = 0.13 \pm 0.05. \]

The experimental beta decay probability, \( \left| \left\langle f \left| m_{\gamma} \right| \text{IAS} \right\rangle \right|^2 \), is hindered with respect to the single particle estimate \( |m_{\beta}|_{SP}^2 = |M_{SP}|_{SP}^2 \) by a factor 100, which we see is due to the hindrance factors 13 for \( m_{\beta} = \int_{x} \xi \) (the same with gamma transition) and 8.
due to cancellation as given in Eq. (7). Furthermore, by using the $\Lambda$ obtained on the basis of CVC theory\textsuperscript{12} and Ahrens-Feenberg approximation,\textsuperscript{11,14} we get from Eq. (7),\textsuperscript{14} $\Lambda_1 = i \sigma \times r \rightarrow r = 0.9 \pm 0.2$. This agrees with the shell model estimate $\Lambda_1 = 1$, indicating nearly the same hindrance factor for both of the $\int r$ and the $\int r ^2 \times r$. In other words, the CVC and Ahrens-Feenberg theories\textsuperscript{1} are consistent with the present experiment as long as we use the shell model value for $\Lambda_1$.\textsuperscript{11,14}

The present work gives a relation between gamma and beta transitions in heavy nuclei and an experimental method of obtaining the matrix elements of the first forbidden beta decay from the gamma matrix element. For obtaining precise values of transition matrix elements a detailed theoretical and experimental study of the interference of the IAS resonance with direct ($p,\gamma$) and giant resonance would be necessary.

(H. Ejiri, S. Ferguson, R. Heffner, D. Perry, and P. Richard)

3 H. Ejiri, K. Ikeda, and J.I. Fujita, to be published.
14 Another choice of $\Lambda_1 = 1.50 \pm 0.2$ for the Eq. (7) can be excluded on the basis of the observed angular distribution of the beta decay from the oriented $^{14}\text{C}e$ by D.D. Hoppes, E. Ambler, F.W. Hayward, and R.S. Kaeser, Phys. Rev. Letters 6, 115 (1961).
15 T. Kotani and M. Rose, Phys. Rev. Letters 1, 140 (1958). A small deviation from this approximation (see Ref. 11) affects slightly the total transition probability of present interest. We have taken this correction into account.
4. SPIN FLIP

4.1 Proton Spin Flip in the $^{12}$C(p,p') Reaction

The probability for spin flip of protons inelastically scattered from $^{12}$C (leaving the latter in its first $2^+$ excited state) has been measured at an incident proton energy of 20 MeV. The motivation for this study has been the continued interest in the proton spin flip reaction, particularly at higher incident particle energies. Recent availability of a code, due to Blair and Sherif, in which the inelastic proton asymmetry and spin flip probability, as well as cross sections, are calculated in the DWBA approximation with a deformed spin dependent potential of the full Thomas form, has allowed comparison of experimental results with theoretical predictions.

The basic experimental procedure, described previously, involves the detection of coincidences between the scattered protons and the de-excitation gamma rays emitted along the quantization axis perpendicular to the scattering plane. Data acquisition has been greatly facilitated by several improvements in the experimental technique:

a. Two liquid nitrogen-cooled particle detectors are used, thus greatly reducing the data collection time and allowing each system to be checked against the other for reliability of operation.

b. Fast coincidence timing is achieved by means of ORTEC 437 Time-to-Pulse-height converters, the coincidence resolution being typically about 5 nanoseconds FWHM.

c. The data is collected directly in the SDS 930 computer, which is used "on-line" each gated and ungated spectrum being stored in a 512 channel array.

d. A parallel gating system enables one to monitor the coincidence timing during the live time of each run. This is accomplished by collecting time spectra in the Nuclear Data 512 analyzer.

The limiting factor in the rate of data collection has continued to be the gamma counter (RCA 7046 photomultiplier tube), which suffers from gain shifts caused by the high counting rates to which it is subjected (typically around 30,000 counts per second). Considerable effort has been expended toward the resolution of this problem, and steps have been taken toward the procurement of another gamma counter (RCA 4522 photomultiplier tube) and the incorporation of a gain stabilization system.

In order to determine the energy at which the spin flip measurement was to be made, excitation functions were first measured at proton scattering angles of $73^\circ$, $145^\circ$, and $165^\circ$. This was done in order to avoid any compound and intermediate resonances which have been observed near these energies. These data are shown in Figures 4.1-1 and 4.1-2 for scattering from the ground state and the $2^+$ level of $^{12}$C. It was decided to make the spin flip measurement at 20 MeV where the cross sections vary smoothly with energy. This choice was further motivated by the availability of elastic polarization and inelastic asymmetry data at
Fig. 4.1-1. \(^{12}\text{C}(p,p')^{12}\text{C}\) Excitation at 73°, 145°, and 165°.

20.2 ± 1 MeV, measured elsewhere. The region around this energy was investigated in smaller energy increments and angular distributions were obtained at 19.5, 20.0, and 20.5 MeV. The angular distributions show little change in this energy range and it seems that, at this energy, resonance effects are relatively unimportant. If spin flip can be attributed to a direct process, the absence of such resonance effects should simplify the theoretical analysis of the results.

Figure 4.1-2. \(^{12}\text{C}(p,p')^{12}\text{C}\) Excitation at 73°, 145°, and 165°.

Figure 4.1-3 shows the measured spin flip probability as a function of CM scattering angle for 20 MeV protons. The results are typical of previously determined spin flip distributions on \(^{12}\text{C}\) at lower energies, except that the forward peak has now become quite distinct and pronounced.

The available data have been compared with theoretical predictions. Parameters for the optical potential were obtained by use of the code ABACUS. These are presented in Table 4.1-1. Set 1 parameters were obtained by fitting only the elastic scattering data. Set 2 parameters were obtained by fitting only the polarization data. Set 3 parameters were obtained by fitting both the elastic scattering and polarization data. Table 4.1-1 also lists the values of the predicted total reaction cross section obtained with each set of parameters. These are to be compared with the experimental value of 138 ± 17 mb at 19.9 MeV. It is clear that Set 2 para-
Table 4.1-1 Optical Parameters $^{12}\text{C}(p,p)\, 20\, \text{MeV}$

<table>
<thead>
<tr>
<th>Set</th>
<th>$V$ (MeV)</th>
<th>$W_s$ (MeV)</th>
<th>$R_R(F)$</th>
<th>$R_I(F)$</th>
<th>$a_R(F)$</th>
<th>$a_I(F)$</th>
<th>$V_{SO}$ (MeV)</th>
<th>$\sigma_R$ (mb)</th>
</tr>
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<td>4.77</td>
<td>1.08</td>
<td>1.22</td>
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<td>0.57</td>
<td>6.53</td>
<td>429</td>
</tr>
<tr>
<td>2</td>
<td>59.15</td>
<td>5.35</td>
<td>1.02</td>
<td>1.33</td>
<td>0.70</td>
<td>0.59</td>
<td>9.79</td>
<td>539</td>
</tr>
<tr>
<td>3</td>
<td>52.47</td>
<td>5.30</td>
<td>1.15</td>
<td>1.22</td>
<td>0.56</td>
<td>0.56</td>
<td>8.73</td>
<td>471</td>
</tr>
</tbody>
</table>

\[ V_{\text{opt}}(r) = -V(1 + \exp^x)^{-1} + i\hbar\frac{d}{dx} (1 + \exp^{x'})^{-1} + V_{\text{coul}}(r) + V_{SO}(x) \]

with $x = (r - R_A^{1/3})/\sigma_R$, $x' = (r - R_A^{1/3})\sigma_I$.

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Fig. 4.1-4. $^{12}\text{C}(p,p)$ elastic scattering at $E_p = 20.0\, \text{MeV}$

Fig. 4.1-5. $^{12}\text{C}(p,p')^{12}\text{C}(4,44)$ inelastic scattering at $E_p = 20.0\, \text{MeV}$
Fig. 4.1-6. $^{12}\text{C}(p,p')^{12}\text{C}$ elastic polarization.

Fig. 4.1-7. $^{12}\text{C}(p,p')^{12}\text{C}^*(4.44)$ inelastic asymmetry.

Fig. 4.1-8. $^{12}\text{C}(p,p')^{12}\text{C}^*(4.44)$ inelastic asymmetry.

Fig. 4.1-9. Spin flip probability $^{12}\text{C}(p,p')^{12}\text{C}^*(4.44)$
meters predict a total reaction cross section which is far outside the limits of the experimental value.

Figures 4.1-3 through 4.1-7 show the comparison of spin flip, elastic scattering, inelastic scattering, elastic polarization and inelastic asymmetry data with the predictions of Sheriff's DWBA code for each set of parameters. The predictions incorporating the full Thomas form of the deformed spin-orbit term are shown. The spin-orbit deformation has been chosen to be equal to that in the central potential, namely $\beta = 0.6$.

The predictions are, in most cases, in semi-quantitative agreement with the data. However, no one set of parameters results in the optimum fits to all the data. The greatest failures seem to be the inability to reproduce the inelastic cross section and the shape of the spin-flip curve, particularly at forward angles.

Calculations have also been performed in which the spin-orbit force is not of the full Thomas form but contains only the radial derivative term (Figs. 4.1-8 and 4.1-9). While these calculations are sufficiently sensitive to differentiate between the two cases, the disparity of the fits with experimental data do not warrant definitive conclusions regarding the form of the spin-dependent coupling potential.

It would seem that, due to the large value of the deformation parameter in $^{12}$C, and the strong excitation of the $2^+$ level, coupled-channel calculations would improve the situation.

(J. Eenmaa, T.D. Hayward, R. Lewis, D.M. Patterson, F.H. Schmidt, and J.R. Tesmer)

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4.2 The $^3$He Spin-Orbit Strength in $^{12}$C as Deduced from $^3$He Spin-Flip

Work is continuing on the $^3$He spin-flip measurements started last year. Measurements have now been made of the spin-flip probability in the reaction $^{12}$C($^3$He,$^3$He')$^{12}$C(4,44) at 22.5 MeV for back angles.

The $^3$He beam intensity available on target has been increased appreciably in the past year (Sec. 12.7) so that it is adequate for measurement at back angles on $^{12}$C. In order to do particle identification at back angles, a 25U solid-state transmission detector was employed. Since this detector passes $^3$He particles with energies above 5 MeV, none of the scattered $^3$He particles of interest were stopped in the transmission detector. The particle identification system used was constructed at the laboratory based on the design of Goulding et al. This system worked quite satisfactorily, even though the particle energies involved were lower than those for which the system was originally designed. Fast timing was found to be a problem. Due to the low energies involved and the large capacitance of the transmission detector, it was found to be impractical to derive a fast coincidence signal from the particle detectors. Cross-over timing was employed instead.

The experimental results are shown in Fig. 4.2-1 and Fig. 4.2-2. Also shown in these figures are the predictions of a DWBA code, which incorporates

**Fig. 4.2-1.** Differential cross sections for the reactions $^{12}$C($^3$He,$^3$He')$^{12}$C and $^{12}$C($^3$He,$^3$He')$^{12}$C(4,44) as a function of center of mass angle. The curves are from a DWBA calculation using the parameters of Set 1 with the spin-orbit strengths indicated.

**Fig. 4.2-2.** $^3$He spin-flip probability in the reaction $^{12}$C($^3$He,$^3$He')$^{12}$C(4,44) as a function of center of mass angle. The curves are from a DWBA calculation using the parameters of Table 4.2-1 with the spin-orbit strengths indicated.
a deformed spin-dependent potential of the full Thomas form, using the parameters listed in Table 4.2-1. The error bars on the elastic and inelastic angular distributions in Fig. 4.2-1 do not include a systematic error of 6% due mostly to target thickness uncertainty. It might be noted that at back angles the statistical errors are less than the size of the points. The error bars on the spin-flip probability in Fig. 4.2-2 are statistical. The experimental spin-flip probability was calculated assuming equal population of the m = 0, ± 2 substates of the 2(444) level in 12C. Since the population of the m = 0, ± 2 substates is not known, this introduces a possible systematic error to each point of + 0.02 or - 0.045.

<table>
<thead>
<tr>
<th>Set</th>
<th>V(MeV)</th>
<th>W(MeV)</th>
<th>WS(MeV)</th>
<th>r₀(f)</th>
<th>r₁(f)</th>
<th>a₀(f)</th>
<th>a₁(f)</th>
<th>s₂</th>
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<td>1.25</td>
<td>1.25</td>
<td>0.65</td>
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<td>1.55</td>
<td>0.597</td>
<td>1.046</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 4.2-1 Optical Model Parameters for 12C(3He, 3He)

The optical parameters of Set 1 were obtained by fitting the elastic data using an optical model code written at this laboratory by W.J. Braithwaite (Sec. 11.6). Even though the code includes a spin-orbit term, this was not used in obtaining the parameters. The curves in Fig. 4.2-1 were calculated with the Set 1 parameters using two-spin-orbit potential strengths. The form of the potential used in the calculation is as follows:

\[ U(r) = V_c(r) - V_0 \eta(r) - \frac{\hbar}{m^c} [\hat{V}_S \frac{\partial}{\partial \hat{r}} g_1(\hat{r}) + \frac{\partial}{\partial \hat{r}} \eta \hat{r} g_1(\hat{r})] \]

where

\[ g_1(\hat{r}) = f_1(\hat{r}, R_1) + \frac{3 f_1(\hat{r}, R_1)}{3 R_1} a_1(\hat{r}) \]

\[ f_1(\hat{r}) = (1 + \exp[(r - R_1)/a_1])^{-1}, \quad R_1 = r A^{1/3} \]

\[ a_1(\hat{r}) = \sum_{\lambda, m} \alpha_{\lambda, m} R_1^{\lambda} \hat{r}^{m\lambda} \]

\[ V_c(r) \] is for a uniformly charged sphere of radius R_c.

The other two sets of parameters were obtained from Nolan F. Mangelson. These parameters were obtained by fitting the elastic scattering of 20 MeV 3He from 12C for forward angles. The inelastic differential cross sections predicted by these three sets of parameters are quite different in magnitude, especially at back angles, and have only gross shape characteristics in common.
The calculations were done to investigate the sensitivity of the spin-flip probability to parameters other than the spin-orbit strength compared to its sensitivity to the spin-orbit strength. The curves in Fig. 4.2-2 are the result of these calculations. As can be seen, the effect of changing the spin-orbit strength from 2.0 MeV to 2.5 MeV is appreciably larger than the effect of the different sets of parameters with the same spin-orbit strength. Thus, even though the measured and calculated inelastic differential cross sections are quite different, it is felt that the comparison of the measured and predicted spin-flip probability is a strong indication that the spin-orbit strength for 22.5 MeV $^3$He on $^{12}$C is between 2.0 MeV and 3.5 MeV.

Work is continuing on this project to obtain better data and calculated fits for $^{12}$C. There is also interest in doing this type of work on heavier nuclei which are better described by the optical model.

(J.G. Cramer, J. Eemann, T.D. Hayward, R. Lewis, D.M. Patterson, J.R. Tesmer)


4.3 Proton Spin-Flip in $^{58}$Ni(p,p') Reaction

Preliminary measurements of the spin-flip probability of 20 MeV protons inelastically scattered from the first 2$^+$ level of $^{58}$Ni have been made. This is a continuation of earlier work at lower energy.1 The procedure is identical to that described in the $^{12}$C measurements.2

Excitation functions for the reactions $^{58}$Ni(p,p)$^{58}$Ni and $^{58}$Ni(p,p')$^{58}$Ni(1.45 MeV) were first measured at laboratory angles of 140° and 165° in order to preclude the possibility of performing the spin-flip measurements near a compound resonance. These data are shown in Fig. 4.3-1. The observed fluctuations are probably of the Eri-son type 3 and their small amplitudes indicate that the reaction, at this energy, is almost entirely direct.

Cross sections and the measured spin-flip probability are shown in Figs 4.3-2 through 4.3-4. Optical model parameters were obtained by use of the optical model code ABACUS. Preliminary
DWBA calculations were performed for the inelastic cross section and for the spin-flip probability using Sheriff's code. In the figures, the dashed lines are those using the full form of the Thomas spin-dependent deformed potential. The solid lines are calculations using only the radial derivative term. The spin-

Fig. 4.3-2. $^{58}\text{Ni}(p,p')^{58}\text{Ni}$ elastic scattering at $E_p = 20.0$ MeV.

Fig. 4.3-3. $^{58}\text{Ni}(p,p')^{58}\text{Ni}^{*}(145)$ inelastic scattering at $E_p = 20.0$ MeV.

orbit deformation used was equal to that of the central potential. In the case of spin flip, the prediction for both cases are high by almost a factor of two at the backward peak, although this magnitude could be reduced by reducing the spin-orbit strength. The fit to the inelastic cross-section is generally of the appropriate magnitude although deviations exist at the intermediate angles. It is clear, nevertheless, that the test of the form of the spin-orbit potential lies at the forward angles of the spin-flip probability, where the deviations between the two forms are largest.

This investigation is being continued with the expectation of reducing the errors in the spin-flip measurements, which are primarily statistical. It is then expected that the $^{58}\text{Ni}$ data will provide a definitive test of the form of the spin-orbit potential for this reaction.

(J. Bemnaa, T.D. Hayward, R. Lewis, D.M. Patterson, F.H. Schmidt, and J.R. Tesmer)
Fig. 4.3-4. Spin-flip probabilities $^{58}\text{Ni}(p,p')^{58}\text{Ni}^{*}(1.45)$

Figure 4.4-la shows the inelastic cross section at 150°. Figure 4.4-lb shows the spin-flip probability while Fig. 4.4-lc shows the spin-flip cross section.

Figure 4.4-lc shows that the spin-flip part of the inelastic cross section fluctuates with energy, possibly more than the inelastic cross section, but that there appears to be no correlation with the inelastic cross section.

A spin-flip excitation function over a much larger energy range would be necessary to determine the compound nuclear contribution to the spin-flip cross section. However, it is evident that experiments measuring spin-flip cross sections near this energy should average over a sufficient number of fluctuations in order to obtain results that might be interpreted by direct interaction theory. (J. Eenmaa, T.D. Hayward, W.A. Kolasinski, R.H. Lewis, D.M. Patterson, F.H. Schmidt, and J.R. Tesmer)

2 Section 4.1 of this report.

4.4 Proton Spin-Flip Excitation Function on $^{58}\text{Ni}$

A proton spin-flip excitation function from 14.750 to 14.800 MeV of the $2^+$ state (1.45 MeV) of $^{58}\text{Ni}$ was measured at 150°(lab). This energy region was chosen due to a large fluctuation in the inelastic cross section at 165°(lab). The spin-flip excitation function, however, was measured at 150°(lab) in order to be close to the maximum of the spin-flip angular distribution. Therefore, the fluctuation is somewhat damped at 150°.
Figure 4a.4-1a  $^{58}$Ni inelastic cross section (1.45 MeV)
4a.4-1b  $^{58}$Ni spin-flip probability
4a.4-1c  $^{58}$Ni spin-flip cross section
5. PHOTONS FROM NUCLEAR REACTIONS

5.1 Gamma Ray Polarization Measurement

During the last year it was realized that the iron of the polarimeter which was used in the gamma ray polarization measurement reported earlier was insufficiently thick for circular polarization analysis of the 4.444 MeV gamma rays from carbon.

No further measurements have been made, but a new polarimeter has been constructed and is presently undergoing tests. However, in order to establish an optimum energy to perform the polarization study the excitation function of the $^{12}C(a,a)$ and $^{12}C(a,a')$ (4.444 MeV) reactions were measured from 21.000 to 23.000 MeV bombarding energy.

The results of these measurements are reported elsewhere in this report. (T.D. Hayward, D.M. Patterson, F.H. Schmidt, and J.R. Tesmer)

2. Section 10.5 of this report (Polarimeter Design).
3. Section 1.1 of this report ($^{12}C$ Excitation Function).

5.2 Search for the Double-$\gamma$ Decay in $^{72}Ge$

The search for a two-photon transition from the $0^+$ first excited state of $^{72}Ge$ has continued. It has been found that the principal sources of background arise not from $^{27}Al + n$ and $^{16}O + n$, as was previously reported, but from other isotopes of Ge. Work is now in progress with a 98.7% enriched metallic $^{72}Ge$ target, improved data collection computer programs, and timing electronics, which will increase the sensitivity of the measurement. (J.P. Allen, W.J. Braithwaite, J.G. Cramer, and C.F. Williamson)

5.3 Gamma Ray Spectra Following Proton Bombardment of Tin Isotopes

By observing the full photon spectrum emitted in nuclear reactions of heavier elements one might hope to obtain two kinds of interesting information: (1) The probability for direct photon emission, i.e., for the emission of photons before a compound nucleus is formed and, (2) the dependence of the average width, $\Gamma$, (for the evaporation of photons from hot compound nuclei), upon the excitation energy. This dependence provides information about the variation of important photon strength functions with energy.

Broad-range photon spectra in heavy element bombardments are rather structureless above a few MeV. This makes them hard to interpret crisply. To help with the problem of interpretation it was decided to do a study of tin. Because of its many isotopes, tin provides the chance of examining a set of nuclei which are expected to behave very differently as regards evaporation and not quite so differently as far as direct emissions are concerned. The projectiles used in our study were protons of $7^4$, $10$ and $14$ MeV. At the first and last of these bombarding energies only $^{112}$Sn, $^{116}$Sn and $^{116}$Sn were examined, but at 10 MeV spectra were obtained for nine tin isotopes ranging in mass from 112 to 124. The photon spectra above 1 MeV were observed at 90° to the beam with a 3" x 3" NaI crystal inside a NaI anti-coincidence annulus. The detector was located at about 100 cm from the targets which were at the center of a thin walled 10" scattering chamber. The accelerator beam was bunched in order to permit time-of-flight discrimination against backgrounds associated with neutrons, induced radioactivity etc. The prompt burst of gamma rays was 7 ns wide as judged from the output of a time-to-pulse-height converter. Most of the background is eliminated if one accepts only those pulses whose time signals lie in a narrow interval around this peak. As a further refinement we subtracted from this gated spectrum the spectrum associated with an equivalent window corresponding to arrival times at the detector, which are slightly earlier than those of the prompt gamma rays. It is important to correct for these backgrounds because as we deduced once before and confirmed with present measurements, about half the observed events in the NaI detector are due to neutrons coming from the target.

It was also necessary to subtract from the observed gamma-ray spectra, the spectra due to oxygen and carbon contamination of the target. For this purpose, C and O background spectra were generated by bombardment of appropriate targets. These two contaminant spectra fortunately contain some conspicuous lines which makes the subtraction more or less straightforward. However, the fact that the oxygen yield is relatively high compared to that of tin at higher energies ($> 5$ MeV), makes the higher energy portions of the tin spectra somewhat uncertain.

The spectra observed at 7 MeV in 1/2 hour runs with a beam of 0.1 ua are shown in Fig. 5.3-1. To keep the figures clear, smooth curves were drawn through the data points and the data points were omitted in the final drawing of the figure. The label on the ordinate is only approximate because of some uncertainties concerning target thickness and because the response function of the NaI detector was only approximately taken into account. It is seen that the spectra are somewhat structured below 3 MeV, but we have seen no indications
of any lines at higher energies. Such lines have been seen in bombardments with neutrons of comparable energies and it may be that they would show up in longer runs or in runs with a higher resolution (e.g., a Ge(Li) detector). Perhaps the most striking feature of the data in Fig. 5.3-1 is the relatively high yield of higher energy photons from \(^{114}\text{Sn}\). For this target the photons above 4 MeV are to be associated with the capture reaction. This is because the Coulomb barrier severely inhibits the reemission of protons below \(E_p \approx 3\) MeV and because the \((p,n)\) 0 value is very negative \((Q \approx -6\) MeV) for this target. The integrated cross-section above \(E_\gamma = 4\) MeV is about 15 mb. When divided by the reaction cross-section, this is more than ten times larger than the correspondingly divided capture cross-section of 7 MeV neutrons for targets near the stable valley with \(A \approx 120\). This fact suggests that the large proton capture cross-section of \(^{114}\text{Sn}\) is due to the extreme proton-richness of this nucleus. Apparently the neutron binding energies are so high that neutrons do not compete as effectively as they normally do in evaporation. Although protons must evaporate more readily from \(^{114}\text{Sn}\) than from heavier Sn isotopes, because of the barrier they still do not evaporate very effectively. In short the tail of the \(^{114}\text{Sn}\) spectrum is to be attributed to the unusually successful competition of photons against protons and neutrons in evaporating from a compound nucleus. These photons are not due to direct reactions. This view is supported by the absence of this tail for the heavier targets where neutron competition is expected to be more important. It is clear from the foregoing that if one wants to look for high energy photons which arise from direct capture, it is best to choose targets on the neutron-rich side of the stable valley.

The spectra from \(^{117}\text{Sn}\) and \(^{119}\text{Sn}\) are due mainly to emissions following \((p,n)\) and \((p,p')\) reactions. As the bombarding energy is raised the upper energy limit for such photons goes up and since they are much more numerous than capture photons, we may expect that the higher energy portions of the spectra observed from the various Sn targets grow more similar as the bombarding energy is increased. This is indeed the case, as one can see from Fig. 5.3-2. Future plans call for a continued search for direct capture photons and for the development of a quantitative account, using evaporation theory, of the spectra in Figs. 5.3-1 and -2. (S.M. Ferguson, I. Halpern, and D.L. Johnson)
Fig. 5.3-2. Preliminary photon spectra from two tin isotopes at 3 different proton bombarding energies. The bold face numbers on each curve give the proton energies in MeV. Note that the scales on the left and right have been shifted by a decade in order to separate the two sets of curves. In interpreting these spectra it is well to keep in mind that the proton reaction cross-sections at 10 and 14 MeV are about 4 and 6 times larger than that at 7 MeV.

5.4 Intensities of Ground State Rotational Band Transitions Following Moderate Energy Compound Reactions in Deformed Nuclei

Compound states of nuclei in the distorted region which have high spins and high excitation energies de-excite by emitting particles and gamma rays, finally populating the levels of the ground-state rotational band. The de-excitation mechanism of the compound states is reflected in the final spin population of the ground band levels, and consequently in the intensities of the ground band transitions. The intensity of the $I \rightarrow I - 2$ ground band transition in an even-even residual nucleus, after subtraction of the intensity of the preceding transition $I + 2 \rightarrow I$, gives the rate at which the ground band level of spin $I$ is populated from outside the band.

It has been found \(^{1-3}\) in reactions involving considerable amounts of angular momentum that the median spin, $I_{1/2}$, at which the evaporation cascade enters the ground band from outside band, is much smaller than it would be if
particles and photons were emitted according to a conventional statistical description. For example, for \((a,xn)\) reactions at \(E_a \sim 40\) MeV, the observed values \(I_{1/2} \approx 6.0\) to 8 (in units of \(\hbar\)) are about half of values estimated with the statistical model.

We report here preliminary work on a model to account for this discrepancy. The basic idea\(^1\)\(^-\)\(^3\) is that the gamma transitions preceding entry into the ground band are not statistical, where by statistical we mean that the transitions from a state of spin \(I\) to states of spin \(I - 1, I, I + 1\) are about equally likely. Instead there is a strong tendency of downward transitions, \(I \rightarrow I - 1, I - 2\), because of the rotational band structure of high lying levels based on the gamma and beta vibrational levels and two quasi-particle states. The intra-band transitions in these higher bands are favored due to the enhanced rotational transition probabilities. Direct transitions to the ground band from band of higher \(K\) are severely hindered due to \(K\) selection rules. The intra-band transitions preceding entry into the ground band result in a shift of the spin population at entry to low spin values. The \(E2\) pattern of the observed angular distributions of the large background of soft radiations and the decay schemes observed upon slow neutron captures in deformed nuclei\(^4\) support the arguments mentioned above.

In its simplest form, the model is based on the assumptions (1) that the ground band is mainly fed from bands with \(K\) quantum numbers 1, 2, ..., \(K_m\), associated with two quasi-particle states and the beta and gamma vibrational bands, (2) that the levels in these bands are populated statistically from higher states, (3) that high \(K\) bands tend to de-excite by intra-band transitions to the band head followed by transitions into the ground band (sometimes via other bands) according to \(K\) selection rules and (5) that the higher lying levels of the vibrational and low \(K\) bands decay through intra-band transitions, but (6) that levels whose spin lies below a critical spin \(I_c\) decay to the ground band directly or via the gamma vibrational band. A schematic diagram of the decay process of the present model is shown in Fig. 5.4-1.

Analytical calculations based on the simple model predict that \(I_{1/2} \approx 7.1 \sim 7.8\) for when the maximum value, \(I_{1/2}\), of the starting angular momentum lies between 20 and 30, and \(I_c\) and \(K_m\) are both equal to 10. These values for \(I_{1/2}\) are in agreement with experimental values \(I_{1/2} \approx 7\) for 40 MeV \((\alpha,n)\) reactions. In addition to the analytical calculations, numerical calculations were carried out where the simple model was refined by assuming branching ratio, \(B = R'(I)/R(I) = (I/I_c)^5\), of intra-band to inter-band transitions from low \(K\) bands. The \(I^5\) dependence of \(B\) arises essentially from the \(E^2\) dependence.

![Fig. 5.4-1. Schematic diagram of de-excitation process of a compound state in energy - angular momentum diagram.](image-url)
of E2 transition probabilities and the proportionality of $E_y$ to $l$. The calculated spin distribution for 40 MeV $(\alpha,\alpha n)$ reactions is shown in Fig. 5.4-2. The statistical spin distribution has clearly been shifted to low spins due to strong downward transitions $I = 1 - l$, $I = 2$ in the high lying rotational bands. Fig. 5.4-3 compares calculated and observed intensities of the ground band transitions. The agreement is seen to be reasonably satisfactory. The measured $I_{1/2}$ values are well reproduced by the model and this successful reproduction is found to be rather independent of details such as the values of $I_m$, $I_0$, and the starting populations of each upper band level as long as $I_m$ and $I_0$ are larger than about 8. To check some of the detailed implications of the model it is planned to investigate experimentally some of the implied intraband and interband transitions.

(H. Ejiri and I. Halpern)

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6. FLUCTUATIONS AND STATISTICAL COMPOUND NUCLEAR REACTIONS

6.1 Investigation of the $^{16}\text{O}^{16}\text{O},\alpha^{28}\text{Si}$ Reaction

The study of this reaction has been continued from last year. The thin target excitation functions were extended from 34.1 to 35.1 MeV of excitation energy in the compound nucleus in order to decrease the finite range of data (FRD) uncertainty associated with extracting information from the Ericson fluctuations. The excitation functions are shown in Fig. 6.1-1. The thick target angular distribution at 35.6 MeV excitation energy was completed.

The thick target angular distribution at 35.6 MeV, unlike that at 34.6 MeV, shows little structure except near 0° and 90° c.m. This is interpreted as being due to interference between $J = 14$ partial waves, which at this energy are no longer negligible, and the $J = 12$ waves which dominate at 34.6 MeV.

The fluctuation analysis, over a larger sample size than previously reported, indicates that the previous analysis may have underestimated the amount of direct interaction.

The auto correlation function may be written

$$R(\varepsilon) = \frac{\langle \sigma(E + \varepsilon) n(E) \rangle - \langle \sigma(E) \rangle^2}{\langle \sigma(E) \rangle^2} = \frac{1 - Y_D^2}{N} \frac{1}{1 + \varepsilon^2/\Gamma_0^2}$$

where $Y_D$ is the ratio of the direct interaction cross section to the total average cross section and the other symbols have been previously defined. The average compound nucleus level width $\Gamma_0$ may be determined from the shape of $R(\varepsilon)$ and from the absolute value of $R(0)$.

Results of the shape analysis for $\Gamma_0$ are given in Table 6.1-1. Corrections have been made for counting statistics, resolution and FRD. The uncertainties are due to FRD.

The shape analysis of $R(\varepsilon)$ does not depend on $Y_D$ or $N$. One may, therefore, determine FRD and resolution corrections from the shape analysis value of $\Gamma_0$, apply these corrections to $R(0)$ and, knowing $N$, calculate $Y_D$ from the absolute magnitude of $R(0)$. For the reaction to the $0^+$ ground state, $N = 1$ at all angles. Calculations for the $2^+$ excited state give $N = 1.54$ at $139°$ and $N = 2.22$ at $269°$. The experimental values of $R(0)$ corrected for counting statistics, resolution, and FRD, and normalized to $N = 1$ are given in Table 6.1-1 with
Table 6.1-1: Fluctuation Analysis of Reactions $^{16}O(^{16}O$,$^{28}Si$ ($0^+$, g.s.) and $^{16}O(^{16}O$,$^{28}Si$ ($2^+$, 1.78 MeV).

<table>
<thead>
<tr>
<th>c.m.</th>
<th>Level</th>
<th>$\Gamma_0$ (keV)</th>
<th>$R(0)$</th>
<th>$Y_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$13^\circ$</td>
<td>$0^+$, g.s.</td>
<td>54 ± 11</td>
<td>0.863 ± 0.330</td>
<td>0.37 ± 0.31</td>
</tr>
<tr>
<td>$13^\circ$</td>
<td>$2^+$, 1.78 MeV</td>
<td>69 ± 14</td>
<td>0.633 ± 0.239</td>
<td>0.61 ± 0.17</td>
</tr>
<tr>
<td>$26^\circ$</td>
<td>$0^+$, g.s.</td>
<td>113 ± 30</td>
<td>0.848 ± 0.423</td>
<td>0.39 ± 0.37</td>
</tr>
<tr>
<td>$26^\circ$</td>
<td>$2^+$, 1.78 MeV</td>
<td>69 ± 13</td>
<td>0.902 ± 0.319</td>
<td>0.32 ± 0.33</td>
</tr>
</tbody>
</table>

Their FRD uncertainties. The values of $Y_d$ corresponding to the corrected values of $R(0)$ are also given. Although the large uncertainties associated with $R(0)$ do not permit a definite conclusion about the presence of direct interaction, the fact that $R(0)$ is less than unity in all four cases indicates that the reaction is not entirely compound nuclear.

To further investigate the possibility of direct interactions as intermediate states, cross correlations between exit channels were evaluated. One may write the symmetrized cross correlation function between two states $i$ and $j$

$$R_{ij}(c) = \frac{\langle [\sigma_i(E) - \langle \sigma_i \rangle] [\sigma_j(E) - \langle \sigma_j \rangle] \rangle}{\langle \sigma_i \rangle \langle \sigma_j \rangle} + \frac{\langle [\sigma_i(E) - \langle \sigma_i \rangle] [\sigma_j(E) - \langle \sigma_j \rangle] \rangle}{\langle \sigma_i \rangle \langle \sigma_j \rangle}$$

To exhibit the correlations it is convenient to remove FRD and $N$ effects by defining a normalized cross correlation function

$$R_{ij}^N(0) = R_{ij}(0)/(R_i(0)R_j(0))^{1/2}$$

which will be equal to unity if the states are completely correlated, zero if no correlation, and negative if anticorrelated. The observed values for $R_{ij}^N(0)$ - e.s. are +0.40 and +0.28 at $13^\circ$ and $26^\circ$ respectively. Although no expressions for the FRD uncertainties are available, they are expected to be large; and, as before, no definite conclusions may be made about the magnitude of $Y_d$. Again, the large, positive values of $R_{ij}^N(0)$ - e.s. indicate the presence of non-compound nuclear processes. If some sort of intermediate state is playing a role, one might expect correlations between the entrance and exit channels. Measurements
The angular cross correlation is given by

\[ R(\theta, \theta') = \frac{\langle \sigma(E, \theta) \sigma(E, \theta') \rangle - \langle \sigma(E, \theta) \rangle \langle \sigma(E, \theta') \rangle}{\langle \sigma(E, \theta) \rangle \langle \sigma(E, \theta') \rangle} \]

As before it is convenient to use a normalized cross correlation function

\[ R_{\theta, \theta'}^N(0) = R_{\theta, \theta'}(0)/(R_{\theta}(0)R_{\theta'}(0))^{1/2} \]

This function has the property that, for any pair of angles, its expected value is unity if compound states with only a single \( J \) contribute. The experimental values of \( R_{\theta, \theta'}(0) = 0.59 \) and 0.78 for the \( 0^+ \) ground state and \( 2^+ \) excited state respectively, support the angular distribution evidence that compound states with only a few \( J \)'s are contributing.

Statistical theory calculations for the differential cross sections and for \( \Gamma_0 \) have been performed. The calculations use a single particle Fermi gas level density expression with a pairing gap of 3.6 MeV for \( e-e \) nuclei and 1.8 for \( e-o \). The adjustable parameters in the calculations are \( a \), the level density parameter, and the moment of inertia. For these calculations the values \( a = A/8 \) and a rigid body gave best agreement between calculations and experiment. These parameter values are consistent with those derived from the inverse reaction \( ^{28}\text{Si}(\alpha, ^{16}\text{O})^{16}\text{O} \).

Two important modifications have been included in these calculations. The angular momentum distribution of the nuclear level density was truncated at a \( J \) value which corresponds to a rotational energy in excess of the available excitation energy. This prevents a catastrophic increase of \( \Gamma_0 \) with increasing \( J \) and decreases the differential cross sections slightly. The states below the pairing gap in the residual nuclei have been included. This increases \( \Gamma_0 \) but is significant only at low compound nuclear excitation energies.

The calculated and experimental cross sections at 90\(^\circ\) c.m. and 35.2 MeV of excitation energy are given in Table 5.1-2.

The calculated and all available experimental values of \( \Gamma_0 \) for the \( ^{32}\text{S} \) compound nucleus are given in Fig. 6.1-2. The size of the rectangles indicates

Table 5.1-2. Comparison of Experiment with Statistical Calculations for \( d\sigma/d\Omega \) (\( \mu\text{b}/\text{sr} \)).

<table>
<thead>
<tr>
<th>°</th>
<th>Level</th>
<th>Experiment</th>
<th>Calc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0(^+), g.s.</td>
<td>10.5 ± 1.3</td>
<td>10.6</td>
</tr>
<tr>
<td>90</td>
<td>2(^+), 1.78 MeV</td>
<td>43.4 ± 3.9</td>
<td>20.6</td>
</tr>
</tbody>
</table>

101
the experimental range of excitation energy in the compound nucleus and the reported uncertainty in $\Gamma_0$. The vertical lines give the calculated $\Gamma_0$ for the compound nuclear angular momenta indicated.

The average value of $\Gamma_0$ reported in this work does not follow the general upward trend of other experimental $\Gamma_0$'s and of the calculated values. As indicated above, the experimental $\Gamma_0$ has decreased from the previously reported value with an increase in the sample size. This is not understood; it may indicate a reaction mechanism other than compound nuclear. (C.J. Bishop, J.C. Norman, R.W. Shaw and R. Vandebosch)

4. We are indebted to Dr. Achim Richter for performing these calculations.
9. This work.

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Fig. 6.1-2. Calculated and experimental compound nuclear level widths. The widths measured over the ranges 13.9-14.2 MeV, 18.75-19.25 MeV, and 26.5-30.6 MeV are from $3^1p(p,\alpha)^{28}Si$ reactions. Those from 29.0-34.4 MeV and 34.1 to 36.1 MeV from $^{16}O(16O,\alpha)^{28}Si$ reactions.
Traditionally one has characterized compound nuclear reactions in the continuum (overlapping resonance region) by simply extending the range of validity of relationships determined in special limiting cases. In particular, the relationship between the channel transmission coefficients $T_c$ and the ratio of channel width to spacing $\Gamma_c/D$,

$$T_c = 2\pi \Gamma_c/D$$

can be derived only for quasi-stationary states, i.e., for $T_c \ll 1$. In the continuum, however, $T_c$ often approaches unity; and the requirement that $T_c$ be no greater than unity places an apparently artificial constraint on the values of $\Gamma_c/D$. Further, it is not clear that the $S$ matrix for this model is unitary. These inconsistencies have been discussed in the literature and Moldauer has derived the expression

$$T_c = 1 - e^{-2\pi \Gamma_c/D}$$

from a class of unitary $S$ matrix models. The average cross sections and cross section fluctuations of Moldauer's models are significantly different from the traditional theory in the two channel case. No calculations have been published for the many-channel case which corresponds to this experiment.

The aim of this experiment was to test statistical model expressions dependent on the above mentioned approximations in the limits of small and large $T_c$ by the comparison of experimental cross sections with model predictions.

The reaction $^{27}\text{Al}(p,\alpha)^{24}\text{Mg}$ was chosen for the following reasons: the compound nucleus $^{28}\text{Si}$ may be excited over a broad range of the continuum with $p$ energies available at the University of Washington three stage FN tandem Van de Graaff accelerator. The first six states in $^{24}\text{Mg}$ are sufficiently separated to be resolved by standard charged particle identification techniques. At the excitation energies reached, the channel to the $0^+$ ground state of $^{24}\text{Mg}$ is well above the Coulomb barrier (large $T_c$'s); the channel to the $4^+$ fifth excited state is below (small $T_c$'s).

Cross sections to the ground and first six excited states of $^{24}\text{Mg}$ were measured at the lab angles of 20°, 50°, 70°, 90°, 110°, 130°, 150°, 170° in steps of 30 keV over the proton energy range of 8 to 10 MeV (19.3 to 21.2 MeV of excitation energy in the compound nucleus). A self supported evaporated $^{27}\text{Al}$ target of 0.32 mg/cm² was used.

The small steps in the excitation function permitted a statistical fluctuation analysis which is not yet complete.

Calculation of the average differential and total cross sections required removal of the statistical fluctuations. The differential cross section was averaged over 0.5 MeV bins. In all cases the angular distribution of this averaged differential cross section was symmetric about 90° c.m., indicating
that the reaction was predominantly compound nuclear. The averaged differential cross sections were then integrated over the angles measured to give the average total cross sections. These average total cross sections were used in the comparison with model calculations and are given by the solid lines in Fig. 6.2-1. The error bars for the ground and first five excited states are due to uncertainty in the target thickness. The larger error in the sixth excited state cross sections is due to counting statistics and a large background subtraction.

The cross section model calculations were done in the spirit of the Hauser-Feshbach model. The differential cross section to a single final state may be written

$$\frac{d\sigma}{d\Omega}(\theta) = \sum_{\text{Leven}} A_{L}P_{L}(\cos \theta) \quad (1)$$

where $A_{L}$ contains the appropriate transmission coefficients, level density expressions, and geometric factors. This may be rewritten in the form

$$\frac{\bar{\Gamma}}{D_{0}} \frac{d\sigma}{d\Omega}(\theta) = \sum_{\text{Leven}} A_{L}^{f}P_{L}(\cos \theta) \quad (2)$$

where $\bar{\Gamma}$ is the average level width in the compound nucleus and $D_{0}$ is the spacing of levels with spin zero in the compound nucleus. The total cross section is then

$$\frac{\bar{\Gamma}}{D_{0}} \sigma = 4\pi A_{0}^{f} \quad (3)$$

In general, different statistical theories give the same results in the limit $T_{c} \ll 1$. The calculations were, therefore, normalized to the fifth excited state experimental cross sections in the following way. From the experimental cross sections to the fifth excited state a value of $\frac{\bar{\Gamma}}{D_{0}}$ was calculated using expression (3). This value is characteristic of the compound nucleus and should be the same for all final states. Then, using $\frac{\bar{\Gamma}}{D_{0}}$, theoretical values of the cross section were calculated for the other final states. The agreement between calculated and experimental cross sections is a measure of the validity of the Hauser-Feshbach model assumptions.

Fig. 6.2-1. Integrated experimental cross sections (eight angles and seventeen energy steps) from the reaction $^{27}\text{Al(p,\alpha)}^{24}\text{Mg}$, and Hauser-Feshbach calculations normalized to the fifth excited state.
The calculated values for the cross sections are given by the dotted line lines in Fig. 6.2-1. There is no systematic deviation of the calculated values from experiment as one moves from closed to open channels. (A.A. Katsanos, R.W. Shaw and R. Vandenbosch)

2. For the detailed form of the $A_0$ coefficients see Sec. 6.4 of this report.

6.3 Fluctuations in the Reaction $^{58}$Ni(p,p') at 15 MeV

The proton spin-flip probability in the reaction $^{58}$Ni(p,p')$^{58}$Ni$^*$ (1.45) at 9.25, 10.5 and 15.0 MeV has been measured and reported previously. These data show that as the proton bombarding energy increases, the spin-flip probability assumes a characteristic backward-peaked angular dependence. This suggests that at sufficiently high energy, a relatively simple direct interaction may be responsible for the spin flip, whereas at lower incident energies, the mechanism which causes the backward peaking is obscured by compound nuclear processes.

There is considerable evidence that in inelastic scattering of protons from $^{58}$Ni at incident energies around 10 MeV, the compound nuclear processes play an important role, while at 15 MeV one might expect the compound nuclear contribution to be considerably less. This is not surprising, in view of the fact that in $^{58}$Ni the Q-value for the (p,n) reaction is -9.3 MeV, and hence relatively few channels are open for CN decay. When the bombarding energy reaches a value several MeV above the (p,n) threshold, the number of decay channels becomes large, the probability for decay into any single channel becomes small, and since the capture cross-section will not change drastically with

![Fig. 6.3-1: $^{58}$Ni(p,p)$^{58}$Ni Excitation, $\theta_{\text{lab}}$ = 120°.](image_url)
energy, one expects that the CN contribution to any one channel will diminish.

In order to determine the amount of CN contribution in the reaction $^{58}\text{Ni}(p,p')^{58}\text{Ni}^*(1.45)$, we have performed a fluctuation study of this reaction. The data obtained consist of excitation curves, where the incident proton energy was varied in 2.5 keV steps in the range from 14.5 to 15.5 MeV, or about 23 MeV in the compound system. The target thickness was about 5 keV, and the Van de Graaff beam energy resolution is estimated to be about 1 keV. Scattered protons were detected at laboratory angles of 120° and 165°. The results are shown in Figs. 5.3-1 and 5.3-2.

These data have been analyzed according to the theories of Ericson and Brink and Stephen.$^{3,4}$ The energy correlation function is defined as

$$C(\Gamma, \delta) = \frac{\langle \sigma(E)\sigma(E+\delta) \rangle}{\langle \sigma(E) \rangle \langle \sigma(E+\delta) \rangle} - 1$$

where $\sigma(E)$ and $\langle \sigma(E) \rangle$ are the measured and energy-averaged differential cross sections at a given scattering angle respectively. For $N$ effective channels

$$C(\Gamma, \delta) = \frac{\Gamma^2}{\Gamma^2 + \delta^2} \frac{1}{N} \left[ 1 - Y_D^2 \right]$$

where $Y_D$ is the ratio of direct to total differential cross section. The quantity $\Gamma$ reflects the "coherence energy" of the compound nucleus, in that all levels within $\Gamma$ contribute coherently to the cross section. Thus $\Gamma$ is equal to the mean level width. The direct-interaction admixture may be obtained by examining the zero intercept of Eq. (2), i.e.,

![Graph of $^{58}\text{Ni}(p,p)^{58}\text{Ni}$ Excitation](image)

Fig. 6.3-2. $^{58}\text{Ni}(p,p)^{58}\text{Ni}$ Excitation; $\theta_{\text{lab}} = 165^\circ$.
\[ C(\Gamma, 0) = \frac{1}{N} (1 - Y_D^2). \] (3)

For purely statistical reactions \( Y_D = 0 \), and thus Hauser-Feshbach calculations may be made for \( C(\Gamma, 0) \), this giving an estimate for \( N \). Any departure of the observed value of \( C(\Gamma, 0) \) from the Hauser-Feshbach prediction may then be attributed to a non-zero value of \( Y_D \).

![Graph](image)

Fig. 6.3-3. Autocorrelation Function for \( ^{58}\text{Ni}(p,p')^{58}\text{Ni}^* \) \( Q = -1.45 \text{ MeV} \), \( \theta_{\text{lab}} = 165^\circ \), \( E_p = 14.5 - 15.5 \text{ MeV} \).

Figure 6.3-3 shows the calculation of the energy correlation function, Eq. (1), for the 2\(^+\) inelastic cross section at 165\(^\circ\). This yields a value of \( \Gamma \approx 11.5 \text{ kev} \) and \( C(\Gamma, 0) = 0.05 \pm 0.01 \). The error is due to the finite range of data. We have not performed Hauser-Feshbach calculations; however, \( N \) is limited to 2 at 180\(^\circ\) due to angular momentum restrictions, which yields a value of \( Y_D = 0.95 \). As one goes toward forward angles \( N \) becomes larger and \( N = 5 \) yields a value of \( Y_D = 0.85 \), which is probably a reasonable lower limit to the direct contribution. (J. Eenmaa, T.D. Hayward, R. Lewis, D.M. Patterson, F.H. Schmidt and J.R. Tesmer)

6.4 Test of Excitation Energy and Odd-Even Dependence of Nuclear Level Densities at High Energies

Recently, level density information covering a large region of excitation energy has become available for even-even nuclei. The excitation energy dependence cannot be satisfactorily reproduced by a conventional Fermi-gas model with a level density parameter $a$, moment of inertia, and pairing energy correction which are independent of excitation energy. The constant temperature and the superconductor level density models are also incapable of producing the level densities over the extended energy regions. Neither can one, using conventional level density formulas, reproduce with Hauser-Feshbach calculations the slopes of the excitation functions and the excitation energy dependence of the statistical decay width $\Gamma$ of the compound nuclei.

The present experiment was primarily performed to determine whether there is a variation of the pairing energy correction between 0 and 23 MeV of excitation energy. Excitation functions for the reaction $^{54}\text{Cr}(p,\alpha)^{51}\text{V}$ were measured between 0.5 and 20 MeV with the proton beam from the University of Washington three-stage FN tandem Van de Graaff accelerator. The compound nucleus $^{55}\text{Mn}$ is an odd-even nucleus one proton removed from the even-even nucleus $^{56}\text{Fe}$, for which level density data is already available. Differential cross sections were measured for the ground and first two excited states in $^{51}\text{V}$ at 0.32 and 0.93 MeV, with spins $7/2^-$, $5/2^-$, and $3/2^-$, respectively. Enriched $^{54}\text{Cr}$ targets (94%) were prepared by evaporation of metallic chromium onto carbon backing. A 0.12 mg/cm$^2$ target was used between 6.5 - 12.0 MeV, and a 0.25 mg/cm$^2$ one between 13 - 20 MeV. The outgoing particles were detected simultaneously by six surface-barrier detectors, from 170$^\circ$ to 40$^\circ$, and in some cases at 20$^\circ$. The detectors were biased to just stop the ground state alpha particles. The alpha particles from the other Cr-isotopes were all lower in energy than those going to the 0.93 level in $^{51}\text{V}$.

The angle-integrated excitation functions obtained are illustrated in Fig. 6.4-1, and angular distributions

Fig. 6.4-1. Angle Integrated Cross Sections and Statistical Model Calculations.
Fig. 6.4-2. Energy integrated cross sections from 7.0 to 7.3 MeV and statistical model calculations normalized to the average of the first and second excited states.

at 7 and 15 MeV are illustrated in Figs. 6.4-2 and -3, respectively. The method of extracting level density information from the cross section and the fluctuation width data requires that the reaction proceed by a compound nucleus mechanism. However, there is evidence for direct processes at certain energies and angles.

If a simple pick-up model is assumed for the direct process of the \((p,\alpha)\) reaction, and a simple \(l_7/2\) configuration for the picked-up nucleons in the target nucleus, the reaction will lead to a low-lying \(7/2^-\) level but not to low-lying \(5/2^-\) or \(3/2^-\) levels. This is because the seniority and angular momentum are assumed to be zero for both the neutrons and protons in the target nucleus. Removal of two paired neutrons and one proton leads to a state with one unpaired proton, therefore proton seniority 1 and angular momentum \(7/2^-\). In the absence of strong direct population, the low lying \(5/2^-\) and \(3/2^-\) levels are expected to be populated primarily by the compound nucleus process. From the angular
distributions and the excitation functions a compound nucleus mechanism is supported for the population of the 5/2− and 3/2− levels between 40°-170°. However, there is some evidence for contributions from direct interactions at smaller angles and higher bombarding energies, indicating some configuration mixing in the wave functions. It should also be mentioned that all three levels in 51V have angular distributions with strong forward peaking in the reaction 50Ti(3He, d)51V, even at 10 MeV. A compound nucleus process is indicated for the production of the 7/2− level below 10 MeV, the fraction due to direct interaction increasing very rapidly above this energy. However, even at the higher energies, although the cross section of this level is a factor of 10-100 larger than the 5/2− and 3/2− levels at forward angles, the cross-section ratios at 170° are approximately the same as predicted by Hauser-Feshbach calculations, indicating that a compound nucleus mechanism predominates at this angle. On the basis of the above considerations, it was assumed that the compound nucleus mechanism is responsible for populating the 5/2− and 3/2− levels in the range 7-16 MeV. Excitation functions with 5 keV steps were measured in the energy regions 7.0-7.3 MeV and 10.0-10.3 MeV and with 10 keV steps in the region 15.0-15.7 MeV. From the fluctuation analysis of the excitation functions the width Γ of the compound nucleus 55Mn was calculated at the mean excitation energies 15.1, 18.0 and 23.1 MeV. From the decay widths Γ, the reaction cross sections and the optical model transmission coefficients T, the level densities (U) of 55Mn were calculated from the equation

\[
\frac{d\sigma_{ab}(\theta)}{d\Omega} = \sum_{L,\Pi} A_L P_L (\cos \theta),
\]

where

\[
A_L = \frac{\sigma_C^2/\Gamma_0 \Pi(U)}{4\pi a^2 (2I_A + 1)(2I_a + 1)} \sum_{S_1, l_1, S_2, l_2} \delta^m_{\Pi} (-1) S_2^2 S_1^2 \frac{T_{l_1} T_{l_2} Z_1 Z_2}{2J + 1} \frac{S_2 S_1}{S_2 S_1} \exp \left[ -J(J + 1)/2Q_C^2 \right],
\]

and \( d\sigma_{ab}(\theta)/d\Omega \) is the differential cross section for the reaction \( A(a,b)B \), \( P_L \) the Legendre polynomial of order \( L \), \( \sigma_C^2 \) the spin cut-off factor of the compound nucleus, \( k_a \) the wave number of the incoming particle, \( I_A, I_a, J \) the spins of the target, the projectile and the compound nucleus respectively, \( S_1 \) and \( S_2 \) the entrance and exit channel spins, \( l_1 \) and \( l_2 \) the incoming and outgoing orbital angular momenta.

The delta function \( \delta^m_{\Pi} \) is the parity conservation factor, and the coefficients \( Z_1 \) and \( Z_2 \) are defined in terms of the Racah coefficient \( W \) and the Clebsch-Gordan Coefficient \( \langle \ell\ell 0|L0 \rangle \):

\[
Z(\ell J Lj; \ell L) = (2J + 1)(2J + 1)\langle \ell\ell 0|L0 \rangle W(\ell J Lj; \ell L).
\]

In Eq. (1) \( \Gamma \) was assumed to be independent of \( J \), and equal to the experimental value of \( \Gamma \).
The results are shown in Fig. 6.4-4, along with similar data for the even-even nucleus $^{56}$Fe. The low energy data on $^{55}$Mn are from the reaction $^{55}$Mn($p,p'\gamma$). The displacement between the level density curves for $^{56}$Fe and $^{55}$Mn is found to be the same ($\approx 2$ MeV) at all excitation energies.

An attempt has been made to reproduce the observed level densities using the Fermi-gas level density formula

$$
\rho(U) = \frac{\tau a^{1/2}}{12\sqrt{2} c^{1/2}(U + t - P)^{1/2}} \exp \left[ 2a^{1/2}(U - P)^{1/2} \right],
$$

(3)

where $a$ is the Fermi-gas constant, $P$ the pairing energy correction, $t$ the thermodynamic temperature given by

$$
U = at^2 - t,
$$

(4)

and

$$
c = J/\hbar^2
$$

where $J$ is the nuclear moment of inertia. It is customary when using this expression to put $P = 0$ for odd-odd nuclei, set it equal to $\Lambda$ for odd-even nuclei and equal to $2t$ for even-even nuclei. If $\Lambda$ is set equal to 2.0 and $a$ is chosen to reproduce the level densities at high excitation energies, the dashed curves in Fig. 6.4-4 are obtained. It can be seen that this formulation does not satisfactorily reproduce the energy dependence of the level density, the latter becoming less than unity at an excitation energy equal to the respective $P$ values for $^{55}$Mn and $^{56}$Fe. On the other hand, if $a$ is chosen to reproduce the low energy data, much too level densities are calculated at high energies (dotted lines). A much more satisfactory fit (full curves in Fig. 6.4-4) can be obtained if one instead somewhat arbitrarily sets $P = -0.5$ MeV for $^{55}$Mn and $P = +1.5$ MeV for $^{56}$Fe. An alternative approach might be to allow the level density parameter $a$ to vary with excitation energy. Although a dependence of $a$ on excitation energy is not without theoretical expectation, this data does not demand it, and its

---

1) $a=6.4$, $p=1.5$
2) $a=6.3$, $p=-0.5$
3) $a=7.1$, $p=3.5$
4) $a=7.0$, $p=1.5$
5) $a=9.1$, $p=3.5$
6) $a=9.0$, $p=1.5$

Fig. 6.4-4. Level Densities for $^{55}$Mn and $^{56}$Fe.
introduction would appear to be required only to patch up the effect of the unrealistic correction for pairing effects.

Statistical model calculations of the excitation functions and fluctuation widths have been performed using a level density parameterization corresponding to the full curves in Fig. 6.4-4. The results are shown in Fig. 6.4-1 and 6.4-5, and are seen to agree very well with the experimental data except where direct processes contribute significantly.

(D. Chamberlin, A.A. Katsanos, R.W. Shaw and R. Vandenbosch)


6.5 The Evaporation of Alpha Particles from Heavy Nuclei in High Energy Alpha Particle Bombardments

One very useful by-product of the run at the Berkeley 88\" cyclotron (see Sec. 1.7) to study the inelastic scattering of alpha particles, was the clear appearance of evaporated alpha particles at the higher bombarding energies. These alpha particles were quite conspicuous at backward angles where their yield was about 10 times larger than the yield of direct alpha particles with the same energies. On the basis of spectral shape it was easy to distinguish the evaporated alpha particles from the direct ones. The evaporated alpha particles were found to be emitted isotopically in the c.m. system to within 5\%, the accuracy which we ascribe to the measurements.

Although the yield of evaporated alpha particles is relatively small (~3\% of the reaction cross section) even at the highest bombarding energy, 90 MeV, it is believed that the observed spectra are particularly well suited
for detailed studies of the statistical evaporation theory. The reason for this view can be outlined as follows. The yield of alpha particles should have an energy dependence on excitation energy which is expected to go roughly as the Boltzmann factor, i.e.

\[ \frac{\Gamma_a}{\Gamma_n} \propto \exp \left( \frac{B_n - B'_a}{T} \right) \]

where \( B_n \) is the binding energy of a neutron to the compound nucleus and \( B'_a \) is the effective binding energy (including the barrier height) of an alpha particle. \( T \) is the nuclear temperature. For a heavy element \( B_n - B'_a \) is about 10 MeV and consequently alpha-particle emission is severely inhibited at low bombarding energy. As \( T \) increases, the alpha-particle yield increases rapidly. As a result, when alpha particles do appear one can be sure that they are emitted either from the compound nucleus initially formed or from a very early decendent, i.e., from a nucleus which has only one or two neutrons less than the original compound nucleus. The fact that the observed spectra correspond to emissions from a limited range of species and excitation energies makes them particularly amenable for study. Normally observed evaporation spectra must be attributed to the superposition of spectra emitted at a great variety of excitations from a long string of species. Such integral spectra can hardly be expected to help pin down critical variables in the theory.

Spectra from a gold target were studied at bombarding energies of 50, 65 and 90 MeV. In addition, Ta and natural Pb were studied at the higher two energies. Since the evaporation spectra are rather structureless, showing but a single broad peak, it suffices to characterize them with their lowest moments. We chose to describe each observed spectrum with three parameters, \( E_p \), the location of the peak, \( \sigma \), the differential cross section at \( E_p \), and \( \Lambda \), the full width of the spectrum at half maximum (see Table 6.5-1). Since it was found that these parameters varied smoothly with bombarding energy and with the atomic weight, \( A \), of the target, the data also provided first derivatives of \( E_p \), \( \sigma \), and \( \Lambda \) with respect to bombarding energy and with respect to \( A \). Thus it was possible to describe the essential characteristics of the observed spectra with nine parameters in all. It was of interest to see to what extent the values of these nine parameters could be accounted for in terms of the conventional statistical theory for particle evaporation.

In this theory the width for alpha particle evaporation is proportional to \( g_a m_a \sigma(E_a) \rho_p / \rho_i \) where \( g_a \) is the spin-connected statistical weight of the alpha particle, \( m_a \) is its mass, \( \sigma(E_a) \) is the inverse cross section for alpha particles at the emission energy and the final factor is the ratio of the nuclear level density in the residual nucleus (after emission of an alpha particle with energy \( E_a \)) to that in the initial compound nucleus. It is not unreasonable to assume that at the high excitation energies involved here, \( \rho \) for nuclei is the same as it would be for a Fermi gas of non-interacting nucleons confined to the nuclear volume. An expression similar to that for \( \Gamma_0 \) describes the width, \( \Gamma_n \), for neutron emission. It is to be emphasized that although there is uncertainty in some of the parameters which enter into the statistical formulas (the critical parameters being those which describe the inverse cross section, the difference in neutron and alpha particle binding energies and the so-called level density parameter), these parameters are by no means free. Therefore any
Table 6.5-1. Values of Parameters Which Characterize the Observed Alpha Particle Spectra.

<table>
<thead>
<tr>
<th>Target</th>
<th>Bombarding Energy (MeV)</th>
<th>$E_p$ MeV</th>
<th>$\Delta$ MeV</th>
<th>$\sigma_p$ $\mu$b/sr MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta</td>
<td>65</td>
<td>19.0</td>
<td>4.8</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>19.6</td>
<td>5.5</td>
<td>1000</td>
</tr>
<tr>
<td>Au</td>
<td>50</td>
<td>19.6</td>
<td>4.1</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>20.0</td>
<td>4.8</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>20.8</td>
<td>5.2</td>
<td>660</td>
</tr>
<tr>
<td>Pb(nat)</td>
<td>65</td>
<td>21.0</td>
<td>5.0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>21.0</td>
<td>5.8</td>
<td>280</td>
</tr>
</tbody>
</table>

A reasonable degree of success at matching the nine independent parameters which characterize the observational data must be regarded as significant confirmation of the details of the statistical theory.

It was found that eight of the nine parameters could be well matched with little effort, i.e., with very acceptable values for the parameters of the theory. For example, it can be shown that $E_p$ occurs where $d \ln \sigma(E_q)/dE_q$ is equal to the inverse of the nuclear temperature which characterizes the spectrum. Because $\sigma(E_q)$ and even $\ln \sigma(E_q)$ and its slope vary very rapidly with $E_q$ in the region of the spectrum peak the cited relationship pins down $E_p$ with considerable precision. The observed values of $E_p$ agreed very well with those deduced using conventional optical model values for $\sigma(E_q)$. In a similar way the $A$ dependence and bombarding energy dependence of $E_p$ were well reproduced.

The spectrum width, $\Delta$, can be shown to be inversely proportional to $[d^2 \ln \sigma(E_q)/dE_q^2]^{1/2}$ and here too the optical model values of $\sigma(E_q)$ provide a good account of the observations.

The one difficulty of the theory occurs in attempts to match the absolute values of the cross sections. Here conventional parameters give results which are three times larger than the observations. An investigation of this problem shows that it is unlikely that the optical model values for $\sigma_\alpha(E_q)$ can be
sufficiently in error to account for the discrepancy. It is found that the absolute cross section is particularly sensitive to differences in the value of the level density parameter relevant for the neutron and alpha particle emissions. For example, a 5% difference in these values would suffice to account for the observations. Such a difference can, for example, arise from a slight and not unexpected energy dependence of the level density parameter.

The details of the matching of theory and observation in these experiments will be given in a publication which is being prepared. One can summarize the results of these comparisons by saying that most features of the observed alpha-particle spectra fit the expectations based on theory so well, that when a relatively small discrepancy does appear, one is encouraged to take the theory seriously enough to ask what parameters one may legitimately perturb to improve the match with observations. One particularly significant feature of the observations is that at these higher bombarding energies there are no apparent magic number or shell effects as there are at lower energies. (J. Chenevert and I. Halpern)
7. NUCLEAR FISSION

7.1 Search for Short-Lived Spontaneous Fission Isomers

Recently it has been observed in certain heavy nuclei that besides the usual prompt fission that occurs when sufficient excitation energy is added, there is also a small component (∼10⁻⁵-10⁻⁷) of delayed fission (τ₁/₂ ∼ μs - min.) from excited states.¹ Nuclei in these excited states have been given the name "spontaneous fission isomers".

Most of the spontaneous fission isomers found have been odd-odd americium isotopes, ²⁴⁴₁,²⁴₂,²⁴⁰₈₉ and ²₃₈₉.² Tentative assignments have been made only in a few other cases.³,⁴,⁵

In view of the large excitation energy (∼3 MeV) of these isomers, together with the observation that they can be produced in reactions where only modest angular momenta are available, it is difficult to attribute the isomerism to retardation of gamma radiations. It has therefore been suggested that they are due to a form of shape isomerism. Calculations by Strutinski⁶ and Nilsson⁷,⁸ predict that secondary minima in the deformation energy between two or more fission saddle points occur over a broad mass region; therefore, spontaneous fission isomers may exist elsewhere besides in the americium isotopes. The half-lives of the isomeric states are very sensitive to parameters in the above-mentioned calculations, thus one should look over a large lifetime range. It is also hard to explain why, with one exception, only odd-odd fissioning isomers are found. We therefore have initiated a search for other fission isomers with the principal goal being to find very short-lived even-even isomers.

Since another study has already been made in the half-life region of 10 μs - 1 hr. over a large mass region by Brenner et al.,⁹ we are concentrating on shorter half-lives in the nanosecond region. The technique we are exploiting is based on the beam structure of the University of Washington 60" cyclotron, which produces beam bursts of 2 nsec width at 88 nsec intervals. We use a fast timing signal from a thin semiconductor fission detector and a signal from the oscillator of the cyclotron to start and stop, respectively, a time-to-pulse height converter. With appropriate delays this allows us to examine times from 10 nsec before the beam burst until 80 nsec after a beam burst. To look for longer-lived isomers, a 100 μg/cm² nickel foil was placed on the downstream side of the target of fissionable material along the beam line to catch recoil nuclei. A semiconductor fission detector was suitably shielded so that it could see only the catcher foil and thus count fission fragments that were from delayed fission of the recoil nuclei. In a preliminary experiment, the 42 MeV α-beam was used to bombard 60 μg/cm² targets of ²³³,²³⁵,²³⁸. The purpose of this experiment was to test equipment for future runs. Since longer counting periods are necessary to look for isomers with the method described above, results are so far inconclusive. As an indication of the sensitivity of the method and the low backgrounds obtained, in a one hour bombardment with 42 MeV α-particles on a ²³⁸ target there were no fission fragments counted in the delayed time range of 10-50 nsec for 3 x 10⁵ prompt fission events.

(R. Vandenbosch and K.L. Wolf)
7.2 Charged Particle Emission in Nuclear Fission

The program of study of charged particle emission in fission has continued. One of the major problems encountered since the last Annual Report is that of a high background in the position-sensitive detector alpha spectrum (see Fig. 7.2-1). Several different experimental studies were undertaken to determine the cause of this background. The incident energy of the protons is 13 MeV and the depletion depth of the detector is 350 microns. Protons of this energy should only lose approximately 2.2 MeV according to range-energy relationships for silicon. The first thought is that this background is due to pile-up; but when one calculates that to reach 10 MeV in pile-up of 2.2 MeV pulses, one would have to pile up 4 or 5 protons. The probability of four proton pile-ups within a resolving time of 2 microseconds and an average counting rate of 20,000 count per second is only 0.00077%. Thus, if the protons only lose 2.2 MeV, one can reject multiple pile-up as the source of the background. But if the proton pulses were larger than 2.2 MeV due to the addition of energy from the depleting region of the detector, it would be possible to account for the background by 2 proton pile-up. This would mean that the proton pulse would have to

Fig. 7.2-1. The circles are the experimental points with chance subtracted of an alpha particle spectrum in coincidence with two fission fragments. The crosses are the chance events measured in the alpha particle counter in coincidence with two fission fragments. The dashed line represents an approximate alpha particle spectrum based on other work.
acquire about 4 MeV from the undepleted region of the detector. Therefore, the energy signal would be made up of a fast signal from the depleted region and a slow signal from the undepleted region. On this assumption, two major changes were made in the experimental set up. One change was to move the detector in-plane. Another change was to incorporate fast timing, using ORTEC time pick-off equipment. The idea here is that the fast part of the signal will be below the discriminator setting while the slow part of the signal won't trigger the pick-off unit.

Improvements have also been made in the computer programs used for data collection. These improvements were necessitated by the addition of another dual ADC to the computer system. One can now read into the computer five associated signals for every ternary event: two fission fragment signals, two signals from the position-sensitive detector, and a signal from a time-to-pulse height converter. With the addition of the time signal, considerable re-writing of the computer programs had to be done to fully utilize this extra piece of information.

Another problem encountered in the experimental set up is that of lining up the scattering chamber so that the beam line goes through the center of two apertures as well as through the center of rotation of the chamber. Since the chamber used is a portable 30 cm chamber which must be put up and taken down with each experiment, a more convenient method of doing the above alignment was designed. The chamber is lined up and the apertures are then lined up independently. Previously the alignment of the chamber and apertures was not independent.
(A.W. Fairhall and D.C. Perry)

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7.3 (d, pf) Angular Correlations

Additional experiments involving the $^{235}\text{U}(d, pf)$ reaction have been performed in order to study the out-of-plane proton fission-fragment angular correlations and the dependence of the in-plane angular correlations on deuteron bombarding energy. The above studies are of particular interest in the excitation energy region where anomalous in-plane angular correlations are seen, as first reported by Specht et al. 5

Figure 7.3-1 shows in-plane and out-of-plane angular anisotropies for the $^{235}\text{U}(d, pf)$ reaction as a function of excitation energy of the compound nucleus. The deuteron bombarding energy for the data in (a) and (b) was 21.0 MeV and was 15.0 MeV for the data in (c) and (d). The proton angle was 90° with respect to the deuteron beam in all cases.

Distorted wave calculations performed as described by Brit et al. 6 and Wolf et al. 7 predict that the in-plane anisotropy should be nearly independent of the K-state distribution of the transition state nucleus for the case of $^{235}\text{U}$ (d, pf). The predicted insensitivity to the K-state distribution is associated with the high target spin of $^{235}\text{U}(7/2)$. Figure 7.3-2(a) shows the differences in
Fig. 7.3-1. (a) and (b) $^{235}\text{U}(d,pf)$ cross section and in-plane anisotropy for a deuteron energy of 21.0 MeV. (c) and (d) In-plane and out-of-plane anisotropy results for a deuteron energy of 15.0 MeV. The abscissa is the excitation energy of the $^{235}\text{U}$ compound nucleus. All measurements were taken at a proton angle of 90° with respect to the beam. The ordinate is given by ratios of $w(\theta,\phi - \phi_p)$ where $w(\theta,\phi - \phi_p)$ is the $(d,pf)$ cross section for a fission fragment direction with respect to $k_d \times k_p$, and $\phi$ is measured relative to the beam axis. $\phi_p$ denotes the $(d,p)$ recoil angle.

Fig. 7.3-2. Calculated in-plane and out-of-plane fission fragment anisotropies as a function of $K^2$, the mean square value of the saddle point $K$-distribution, assuming a Gaussian distribution. The DWBA code T-Sally was used to generate reaction amplitudes for the $(d,p)$ reaction with a deuteron energy of 15.0 MeV and a proton energy of 13.0 MeV. The dashed and solid lines are for spin 1/2 and spin 7/2 target nuclei, respectively.

The calculated in-plane anisotropy for $(d,pf)$ on spin 7/2 and spin 1/2 target nuclei as a function of the mean square value of $K$, $K^2$, for a Gaussian $K$-state distribution. Statistical tensors were calculated from reaction amplitudes generated by the DWBA code T-Sally for a deuteron energy of 15.0 MeV and a proton energy of 13.0 MeV. Optical model parameters were determined from elastic scattering data for 15.0 MeV deuterons and 13.0 MeV protons on $^{239}\text{Pu}$. One would expect that the $K$-state distribution of $^{236}\text{U}$ is similar to that of $^{240}\text{Pu}$ within a few MeV above fission threshold since both are even-even fissioning nuclei. Thus, assuming that the $K$-state distribution of $^{236}\text{U}$ is similar to that of $^{240}\text{Pu}$ and that there is a negligible change in the $(d,p)$ transferred orbital angular momentum distribution and reaction mechanism with excitation energy, DWBA calculations indicate that the in-plane anisotropy should be nearly constant as a function of excitation energy. The predicted values for the in-plane anisotropy are $\sim 1.2-1.3$ for 15 MeV deuterons and somewhat larger for 21 MeV deuterons. The experimental data for 15 MeV, unlike that for 21 MeV, doesn't exhibit such simple behavior.
The in-plane anisotropy for 15 MeV is smaller than the predicted value below about 7 MeV of excitation energy and even becomes considerably less than unity below the fission threshold. Explanations of this anomalous in-plane anisotropy have been given elsewhere and will be discussed only briefly here. Two different mechanisms have been suggested for the anomalous in-plane anisotropy. First, the mechanism of Specht et al. depends on populating only certain single particle states, along with fission barrier penetration or K-conservation during passage from the capturing configuration to fission saddle point. In a recent joint letter with J. Unik, C. Stephen, and J. R. Huizenga of the Argonne National Laboratory, we have suggested an alternative explanation for the anomalous anisotropy which incorporates the dependence of the Coulomb barrier on the orientation of the deformed target nucleus. This affects the probability for both the deuteron to reach and the proton to leave the nuclear surface where the (d,p) reaction occurs, and favors the probability of a reaction occurring when the target nucleus happens to have its principal axis oriented along the recoil axis as is illustrated in Fig. 7.3.3. The high target spin (7/2) which is parallel to the principal axis of the deformed nucleus will be parallel to the recoil axis and thus for low angular momentum transfers the target spin will dominate the angular distribution of fission fragments, resulting in a less than unity in-plane anisotropy.

To explain the dependence of the anisotropy on excitation energy for the 15 MeV data, one must invoke fission barrier penetration. The transferred angular momentum from the (d,p) reaction will tend to wash out the target spin effect. Very high angular momentum transfers couple to the target spin to give high values of the compound nuclear spin, J. These high spin states will decay principally by gamma emission below fission threshold because of the rotational level spacings of the transition state nucleus and because of the increase of $T_1/T_2$ with J. Thus, most of the fission cross section in the sub-threshold region is from those states that were formed with low angular momentum transfers.

Unlike the results for 15 MeV deuterons, the anisotropy at low excitation energies for 21 MeV deuterons shows no tendency to become less than unity. This can be attributed to two factors. In the first place, at this deuteron energy both the deuteron energy and the proton energy are well above the Coulomb barrier, and the interaction probability should not be sensitive to the target nucleus orientation. Second, the average orbital angular momentum transfer has become large compared to the target spin.

The out-of-plane anisotropy can also give information about the mechanism that causes the anomalous in-plane anisotropy. If certain single particle states

![Graph showing the anisotropy for 235 U(p,d) reaction at 15 MeV with E_p = 15 MeV.](image)

**Fig. 7.3-3.** Sketch indicating possible trajectory and target orientation in (d,p) stripping reaction.
are populated to produce the less-than-unity in-plane anisotropy, as proposed by Specht, one would expect a close correlation between the in-plane and out-of-plane anisotropies. As shown by the results of the calculations presented in Fig. 7.3-2, the functional dependence of the in-plane anisotropy on $K_0^2$ is accompanied by a similar dependence for the out-of-plane anisotropy. This is more apparent for the case of a spin $1/2$ target where the predicted dependence of the anisotropies on $K_0^2$ is more sensitive. Also, our calculations show that for orbital angular momentum transfer from $\lambda = 1$ to 4 there is very little dependence of the ratio of the in-plane anisotropy to the out-of-plane anisotropy on the amount of each $\lambda$-value contributing. If the anomalous in-plane anisotropy were caused by populating certain single particle states, we would therefore expect that as the in-plane anisotropy decreases with decreasing excitation energy, the out-of-plane anisotropy would decrease similarly.

The mechanism based on the deformation of the target nucleus predicts that the out-of-plane anisotropy should become nearly isotropic in the anomalous region and not be closely correlated with the in-plane anisotropy because the fission fragment angular distribution is governed by the target spin in this region.

The statistical uncertainties of the 15 MeV data in the anomalous region as shown in Fig. 7.3-1(c) and (d) are too large to definitely say that the data is inconsistent with one mechanism or the other. However, the out-of-plane anisotropy doesn't seem to be closely correlated with the in-plane anisotropy below fission threshold. While the in-plane anisotropy is decreasing from a value of 1.0 at 5.6 MeV of excitation to 0.6 at 5.4 MeV, the out-of-plane anisotropy is unchanged within experimental error.

Another experiment exploring the role of the deformed target nuclei is discussed elsewhere in this report.9

Above 7 MeV of excitation in the 15 MeV data, the in-plane anisotropy is in approximate agreement with the calculation, but the out-of-plane anisotropy is much larger than one would expect from the calculation. The origin of the large out-of-plane anisotropy is not fully understood. Perhaps it is related to the fact that excitation energies above 6.5 MeV correspond to the transfer of an unbound neutron by the $(d,p)$ reaction. The calculation of reaction amplitudes by the code T-Sally6 requires that the transferred neutron be bound. The calculation may not be valid when extrapolated into the unbound neutron region. It has also been observed in the case of $^{239}$Pu($d,p$) that the out-of-plane anisotropy becomes comparable to the in-plane anisotropy in the unbound neutron region.

(R. Vandenbosch and K.L. Wolf)

1 Nuclear Physics Laboratory Annual Report, University of Washington (1965), p. 22.
7.4 Competition between Neutron Emission and Fission at Moderate Excitation Energies

Work is progressing on the experiment discussed in the 1966 and 1967 Annual Reports.

One of the big problems that confronted us was a lack of good energy resolution in the neutron counter. By carefully polishing a one inch thick piece of NE102 plastic scintillator and coating it with many layers of reflector paint (NE550) we were able to obtain an alpha resolution of almost 9% on 8.78 MeV alphas. We discovered a factor of two variation in pulse height as a collimated source was moved from the center of the scintillator to the edge. This pulse height variation with position results in poor energy resolution for an uncollimated source. To reduce this non-uniformity we placed a one inch thick light pipe of polished lucite plastic between the scintillator and the phototube face. This produces a more uniform light distribution at the photocathode and eliminates the pulse height variation with source position. The resolution at the present time is such that the peak to valley ratio of the 60 keV gamma ray from $^{241}\text{Am}$ is about 1.4.

By using ORTEC heavy ion detectors for the fission fragments we have been able to reduce the time resolution of the neutron time-of-flight system to less than 2.5 nsec as measured by the FWHM of the prompt gamma peak. It was found that care must be taken when detecting neutrons in the direction of one of the fission fragments because a fission counter shields the neutron counter from the target. We have seen a reduction in the neutron yield of up to 35% due to absorption and scattering by the fission counter. One way of minimizing this effect is to use large transmission-mounted detectors as fission counters.

Recently more data has been taken on $^{236}\text{U}$ with 11.5 MeV protons. Three pieces of information are collected for each event: the energy of the two fission fragments as measured by solid state detectors, and a time from the neutron time-of-flight system. Each event is stored on magnetic tape for later analysis. To analyze the data we proceed as follows: The $0^\circ$ neutron lab spectrum is composed of several parts, the contribution of neutrons from the fragment coming toward the neutron counter, the contribution from the fission fragment going away, and the contribution from pre-fission neutrons. Initially assuming that all the neutrons seen at $0^\circ$ come from the fragment coming toward the neutron counter, we transform the data to the center-of-mass system and then to $180^\circ$ in the lab to predict what fraction of the $0^\circ$ experimental data could be due to neutrons emitted from the fission fragment going the other way. We subtract this quantity from the $0^\circ$ data and transform the remainder to $90^\circ$ in the lab. This then is subtracted from the $90^\circ$ experimental data to obtain the contribution due to pre-
fission neutrons. By subtracting this pre-fission contribution (assumed isotropic) from the 0° data we get a better estimate of the post-fission part of the 0° data and can iterate the transformations until convergence in the post-fission and pre-fission spectra occurs. From this transformation procedure we can extract the number of post-fission and pre-fission neutrons and their spectra. These numbers are related to \( \Gamma_n/\Gamma_f \) (ratio of the probability of neutron emission to the probability of fission) and our object is to study the dependence of this quantity on excitation energy. We might add that it is better to start with the assumption that the neutrons at 0° are all post-fission than to assume that the neutrons at 90° are all pre-fission. Considerable time has been spent in writing computer codes which will allow the above type of analysis to be done on our SDS 930 computer. These codes include corrections for such things as: fission fragment flight times, grid fluctuations, gamma ray flight times, pulse height defect in the fission detectors, and counting efficiency of the neutron counter. (C.J. Bishop, I. Halpern, R. Shaw, and R. Vandenbosch)

1 Nuclear Physics Laboratory Annual Report, University of Washington (1966), p. 70.
8. OTHER NUCLEAR PROCESSES

8.1 Proton-Proton Bremsstrahlung

Although no data has been taken yet in the proton-proton bremsstrahlung (PPB) experiment, work on instrumentation for it has been done in two main areas: construction of a gas target system and electronics. The gas target was specifically designed for use with protons of energy 15 or more MeV incident on hydrogen gas at pressures up to three atmospheres. A gas target system built earlier at this laboratory\(^1\) produced a large background of particles with energies ranging from zero up to the full beam energy. This background appeared to be caused by multiple scattering in the entrance foil. Consequently, in the design of the new target (see Fig. 8.1-1) the entrance foil was moved further upstream, and the multiple scattering from both the foil and the gas was removed by a series of apertures. These apertures were large enough so that particles scattered through less than the r.m.s. multiple scattering angle (calculated using Molière's formula\(^2 , 3\)) would not hit them.

The windows of the target are both 0.00027 cm thick heat treated Havar foil,\(^4\) glued in with a flexible epoxy.\(^5\) The weakest part is the cylindrical exit-viewing foil, because of its large area. There are two exit-viewing foil assemblies, one with radius 1.27 cm and one with radius 1.90 cm (see Fig. 8.1-1). The maximum pressures that these foils have held are 3.35 and 2.05 atmospheres.

With 15 or more MeV protons incident, the energy straggling and multiple scattering produced by hydrogen are small enough so that the beam can pass through a considerable thickness of gas without adverse effects. Even with three atmospheres of hydrogen in the cell, the major contribution to the multiple scattering is the entrance foil, although a gas of higher Z might contribute appreciable multiple scattering. The total beam energy straggling due to
Fig. 8.1-2. A view of the gas target and a two-slit counter viewing system mounted in the 60-in. scattering chamber.

the entrance foil and three atmospheres of hydrogen was calculated to be less than 30 keV, for 15 MeV protons incident.

Two systems of viewing slits have been made for use with the gas target, one system for each arm of the 60-in. scattering chamber. Each system consists of two stands, the first holding two vertical "shutters" and a horizontal "sill" which form the front window and the second holding two shutters to define the vertical part of the back window, an aperture which defines the top and bottom, and the detector. The shutters can be set to give various width slits and the two stands can be placed at various radii in the scattering chamber, so the system is quite flexible. Fig. 8.1-2 shows the arrangement of the target and a slit system.

The spectrum of elastic scattering from hydrogen is very clean compared to that obtained with the older gas target system. The effects of the front and rear slit edges on the background were studied by changing the slit widths separately and observing the effect on the background. Since narrowing one slit reduces the background from the other but not from itself, and since the elastic yield is related to the two slit widths, the effects of each slit can be determined this way. For the front slit 9.8 cm and the back one 29.5 cm from target center, with equal slit widths, the contributions to the background from the two slits are about equal. Figure 8.1-3 shows a spectrum obtained in this geometrical configuration with the slit thicknesses 1.15 mm. With larger slit spacings one would expect the peak-to-valley ratio to improve.

The primary electronic problem in the PFF experiment results from the high elastic rates necessary to obtain sufficient statistics in the bremsstrahlung. The bremsstrahlung events are identified by two protons of appropriate energy in coincidence at angles where there are no elastic-recoil coincidences kinematically allowed. The bremsstrahlung events are lower in energy than the
elastic events at the same angle, so accidental coincidences between elastic events should not be a problem unless each of the particles involved has lost additional energy, i.e., through slit scattering, double scattering, or a nuclear interaction in the detector. It is expected that with standard coincidence techniques giving about 10 nsec resolving time, the limitation on the count rate will not be accidental coincidences but deterioration of resolution in the amplifier.

The main work done to combat this problem consists of the improvement of a pile-up rejector circuit which had already been built at this laboratory and of the testing of various amplifiers under conditions simulating the PPB experiment.

The pile-up rejector is triggered by an appropriate fast timing pulse from each detector. The first timing pulse sets the first of a series of flip-flops and triggers a univibrator whose pulse width is variable from one to 20 microseconds. At the end of the univibrator pulse, if only the first flip-flop is set, the unit produces a gating pulse and resets the flip-flop. If more than one flip-flop is set, the unit produces no gating pulse, but just resets itself. Thus the only gating pulses will be for single energy pulses which are separated from earlier and later pulses by more than the width of the univibrator pulse. In addition, there is a circuit incorporated into the pile-up rejector that allows the user to require a coincidence with an external pulse in order to produce an output. The pile-up rejector can distinguish pulses that are more than 75 nsec apart. Pulses closer than that are treated as one pulse. The effect of the pile-up rejector on a pulser peak in the presence of $3.8 \times 10^4$ counts/sec from a $^{212}$Pb (ThB) alpha source is shown in Fig. 8.1-4.

A number of amplifiers were tested to determine the effect of a high count rate singles background on the spread in amplitude of a low rate pulse that could be separated from the background by coincidence methods. Two different methods were employed to do this: 1) a hot alpha source produced the singles counts and a pulser produced the slow rate pulse, and 2) the singles were

![Image](image-url)
produced by scattering the Van de Graaff proton beam from a thick target of titanium on a copper backing and the slow rate pulse was produced by the elastic scattering from hydrogen dissolved in the titanium. The elastically scattered protons were identified by forming a coincidence with the recoil proton which was detected in a counter that subtended a much smaller solid angle than the one whose output was being studied. Singles rates of up to $10^3$ counts/sec, as measured with a Canberra model 1435 discriminator, were studied.

The amplifiers studied included the Canberra model 1417, the Tennelec TC200, the Ortec 440, the Ortec 220, and the Hamner NA120. The Tennelec and Canberra were far superior to the others in terms of full width at half maximum, full width at tenth maximum, and general appearance of junk at the sides of the peak. The Canberra was the only amplifier tested with the beam. Fig. 6.1-5 shows the dependence of full width at half maximum on the singles rate. In this test the pile-up rejector was set for three or for four microseconds, as indicated on the figure. The planned angular resolution of the proton counters will define the gamma-ray's angle to within about 20°. A proton energy uncertainty of about 200 keV will not seriously alter the gamma-ray angular uncertainty. However, better proton resolution would be desirable to facilitate background subtraction.

(J.C. Cramer, I. Halpern and D.W. Storm)

Fig. 6.1-5. The resolution (FWHM) plotted against the counting rate for the Canberra model 1417 amplifier with pile-up rejector as described in the text. The resolution of this detector was poor to start with.

3. The calculation used a computer program by J.B. Ball, ORNL-3311, (1963).
5. General Mills Chemical Versamid 125 and Shell Chemical Epon Resin 828, mixed about 2:1.
8.2 Nucleosynthesis During Silicon Burning

It is generally believed that in the evolution of stellar interiors a stage is reached in which the matter is, to a large extent, in the form of the tightly bound nuclear species $^{28}$Si. This stage is followed by a rise in stellar temperatures, resulting in the gradual photodisintegration of the $^{28}$Si, with the release of alpha particles and protons. The chain of reactions of these particles on $^{28}$Si and heavier products results in the buildup of nuclei to the iron group.

A detailed analysis of the evolution of a gas of pure $^{28}$Si was undertaken, under the simplifying assumption that the gas remains at constant temperature and density during the evolution. It was found possible to describe the process in terms of a succession of quasi-equilibrium configurations in which $^{28}$Si and heavier nuclei are in equilibrium under the exchange of nucleons and alpha particles. The successive configuration can be assigned a well defined time scale, and are characterized by increasing alpha-particle densities, by increasing concentrations of the iron-group nuclei, and by a decreasing concentration of $^{28}$Si. For temperatures and densities in a band extending from $3.8 \times 10^9$ °K and $10^7$ gm/cm$^3$ to $5.0 \times 10^9$ °K and $10^5$ gm/cm$^3$, it was found that the calculated abundances when about 65% of the $^{28}$Si has been consumed correspond to important aspects to the natural solar-system abundances. The overall process is strongly exoergic. The observed natural abundance peak at A = 56 results from a high concentration of $^{56}$Ni, which later is converted to $^{56}$Fe through electron capture and beta decay.

In view of the character of the agreement between the calculated and observed abundances, and in view of the emergence of silicon burning as a natural stage in the history of a thermonuclear gas, it appears plausible to attribute the natural solar system abundances of the A = 4n nuclei (A = 28 through A = 56) and the dominant nuclei in the lower part of the iron group (A = 47 through A = 57) to the results of such quasi-equilibrium $^{28}$Si burning sequences. Subsequent secondary processes, such as neutron capture, are responsible for the abundances of the remaining, less abundant, nuclei in the mass region A = 28 to A = 60.

This study was initially undertaken at the California Institute of Technology, in collaboration with D.D. Clayton (on leave from Rice University) and W.A. Fowler (California Institute of Technology), while one of the investigators (D. Bodansky) was on leave from the University of Washington. The study was continued while the authors were variously at the University of Washington, The Institute of Theoretical Astronomy (Cambridge, England), Rice University, and the California Institute of Technology. A preliminary report of this work has been published and a more detailed report has been submitted for publication. (D. Bodansky)
8.3 Test of Time Reversal Invariance in the $^{24}$Mg + d $\rightarrow$ $^{25}$Mg + p Reactions

This experiment was discussed in detail in the previous Annual Report. Remaining aspects of the analysis have been completed, and a full report has been prepared for publication. The principal results of the experiment were not changed by the further analysis: namely, that no evidence was found for a violation of time-reversal invariance, that in the most accurate comparison the experimental results for the inverse reactions were in agreement within an uncertainty (standard deviation) of 0.3%, and that the ratio of the T-noninvariant to T-invariant reaction amplitude is probably less than 0.3%. (D. Bodansky, W.J. Braithwaite, D.C. Shreve, D.W. Storm and W.G. Weitkamp)

6.4 The Dependence of the Reaction Cross Section Upon the Orientation of a Deformed Target Nucleus

In a recent study of the $^{235}$U(d, pf) reaction\textsuperscript{1,2} it was found that the angular correlation between proton and fission fragment was anomalous in character. It was suggested that the anomaly arose because of the deformation of the target nucleus and its relatively large spin. Because of the deformation, target nuclei with particular spatial orientations were more likely than others to be involved in a given (d, p) event. The angular distribution of fission fragments emitted in such events provide evidence for these orientation effects through the dependence of such distributions on the nuclear spin and the deuterons bombarding energy.

It appeared that it might be possible to study this effect in a simple angular distribution experiment instead of a correlation measurement. It had earlier been found in this laboratory and elsewhere\textsuperscript{3} that ground-state-band radiations from deformed even-even residual nuclei which are produced in nuclear reactions have strongly anisotropic angular distributions. These distributions can be shown to provide a good measure of the angular momentum orientations of the excited compound nuclei initially formed in the reactions.

Thus if one has a prolate target nucleus, the chance that a low energy charged projectile will form a compound nucleus should be larger for nuclei aligned parallel to the incident beam than for nuclei perpendicular to it, due to the difference in the Coulomb barrier for the two orientations. If the
probability for compound nuclear formation depends, in this way, on target orientation, it follows that the initial compound nuclei will be aligned with their spins mainly back and forth along the beam direction. As has been indicated, a measurement of rotational photon distributions provides a good test for such alignment.

The reaction chosen for study was $^{176}\text{Lu}(p,n)^{176}\text{Hf}$ because of the very large deformation (6 $\sim$ 1/4) and spin (7$^+$) of the target nucleus. For incident protons with energies in the neighborhood of the barrier, the compound nuclei formed should have their spins in the beam direction and when they emit E2 radiations, these radiations should be off favoring the direction perpendicular to the beam. At higher bombarding energies, when the orbital angular momentum involved in the reaction exceeds that of the target, the initial total spin vectors tend to be oriented perpendicular to the beam and the radiations should therefore emerge mainly at 60° and 180° to the beam. Anisotropies of this latter kind are well known whereas those with maxima at 90° had never been observed.

As an aid in planning and interpreting the experiment, an approximate calculation of the expected angular distribution and its dependence on bombarding energy was performed. The first step in this calculation was the determination of the effective potential barrier along the major and minor axes of the deformed nucleus. The Coulomb potential was calculated for a uniformly charged prolate spheroid with $\epsilon = 0.24$. To this was added a diffuse surface nuclear potential which followed the deformation, and for different values of $l$, an appropriate centrifugal potential. The resulting potentials for the two orientations are shown in Fig. 8.4-1. We then computed the penetration through these one-dimensional barriers. The penetration for nuclei which happen to be oriented at 60° to the beam was taken to be that computed along the major axis. That for nuclei at 90° was that along the minor axis. (The validity of this scheme for estimating penetrabilities as a function of orientation is not known, but in view of the small number of partial waves involved it may be inherently too classical.) For intermediate angles a quadratic interpolation was used.

To obtain the spin distribution ($J_z$ as well as $J$) of initial compound nuclei, the orbital angular momenta were coupled to the target spin. For simplicity, the proton spin contribution was ignored. In the same way the small angular momentum of the evaporated neutron was ignored. The

Fig. 8.4-1. Proton potential barriers for prolate spheroids whose major axis is either parallel or perpendicular to the beam direction.
angular momentum distribution at entry into the ground state band was determined by imagining that a single dipole emission carries the initial compound nuclei into the rotational states. This is certainly not what happens, but is probably a good enough procedure for present applications because one can show that whatever radiations take place, they do not seriously reorient the directions of the initial angular momentum vectors. Thus the distribution in $J_z$ at entrance into any $J$ of the ground state band is rather insensitive to the detailed nature of the photon cascade preceding such entrance. Having determined the $M$ distribution for entry into each $J$ of the ground band, it was possible to compute the expected quadrupole angular distributions for each of the ground state transitions. In carrying out these computations, account was taken of the effects of the cumulative feeding of lower rotational states by higher ones. The results of a typical calculation for the $6 \to 4$ transition are shown in Fig. 8.4-3. Also shown is the distribution expected for a spherical target nucleus having the same spin as the deformed target. The variation with incident proton energy has also been investigated, and it was found that the predicted anisotropy decreases slowly as the incident energy increases from 6 to 10 MeV.

The photon angular distribution measurements were made at the tandem accelerator with a 20 cc Ge(Li) detector using a 10 in. thin-walled scattering chamber. The detector was mounted in a lead shield on a moveable support outside the chamber. It could be rotated to angles between 25° and 155°. The detector rotation axis was checked to be aligned with the target by observing isotropic distributions (to $\sim 1\%$) for a radioactive source mounted in the target and for the radiation from the 0.89 MeV spin 1/2 state of $^{27}$Al produced in a bombardment.

The target was 700 µg/cm$^2$ of enriched (98%) $^{176}$Lu$_2$O$_3$ prepared by molecular plating on 100 µg/cm$^2$ of nickel backing. The nickel was shown to contribute no discrete lines in the regions of interest.

The beam was focused through an 8 mm carbon aperture placed 50 cm upstream from the target. The aperture was electrically insulated and the beam current it intercepted was monitored at the control console. At a typical beam current of 1 µA the aperture current was less than 0.1 nA.

The product of target thickness and beam current was monitored by a charged particle detector. The ratio of monitor counts to total charge varied by 1% or less provided the aperture current was minimized by careful focusing.

It is known that $^{176}$Hf has isomeric states ($t_{1/2} \sim 10$ µsec) which feed the ground state rotational band. For some of the runs the beam chopper was set to pass 40 nsec beam pulses every 400 nsec. Use of a time pick-off unit and a time-to-pulse height converter permitted the observation of delayed radiations. About 25% to 35% of the total strength of the $6^+ \to 4^+$ radiation was found to be delayed. It is necessary to subtract the delayed radiations from the data because the isomeric states are sufficiently long-lived to allow for nuclear reorientation. This correction has not yet been made for most of the data presented in this report.

The observed spectra were collected and analyzed by the SDS 930 computer.
using the program described in Sec. 11.7 of this report.

Figure 8.4-2 shows a portion of the spectrum observed at an incident proton energy of 7.5 MeV. The intensity of the $6^+ \rightarrow 4^+$ transition is strong enough

![Graph](image)

Fig. 8.4-2. A gamma-ray spectrum produced by the bombardment of $^{176}$Lu by 7.5 MeV protons. The detector is a 20 cc Ge(Li) device with 4 keV resolution. so that its relative differential cross-section can be determined within a statistical error of only 2 or 3% in about 1/2 hours of beam time. The $4^+ \rightarrow 2^+$ line is of course even stronger, but unfortunately some small nearby peaks introduce some uncertainties in estimates of its relative intensity. The $8^+ \rightarrow 6^+$ transition was judged too weak to analyze. This is also true of the heavily converted $2^+ \rightarrow 0^+$ transition which suffers also from a background of x-rays.

Good angular distributions were obtained for both the $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ lines at proton energy of 7.5 MeV. At this energy at least two runs were made at each of $25^\circ$, $40^\circ$, $55^\circ$, $75^\circ$, $90^\circ$, and $155^\circ$. The angular distribution of the $6^+ \rightarrow 4^+$ line is shown in Fig. 8.4-3 along with the rough theoretical estimate. The distribution of the $4^+ \rightarrow 2^+$ line was very similar. It is seen that the
Fig. 8.4-3. Angular distributions of E\textsubscript{2} gamma-rays following the (p,\gamma\gamma) reaction, at a proton energy of 7.5 MeV. The full curve is the predicted result for a deformed target nucleus. The dashed curve is the predicted result for a spherical target nucleus. The data points are from the $6^+ \to 4^+$ transitions in $^{176}$Hf.

25°, 90° and 155° for proton energies of 6 and 9 MeV. The anisotropy observed in the $6^+ \to 4^+$ transition is plotted in Fig. 8.4-4 as a function of bombarding energy along with an approximate theoretical estimate.

It is clear from the size of the error bars and from the character of the theoretical estimate described above, that both the experiment and the theory will need further work. It seems, however, that the effect in question has been observed. That is, it appears that one can effectively align a system of deformed nuclei by making use of the dependence of their probability for absorbing a charged projectile on their orientation. (H. Ejiri, S.M. Ferguson, I. Halpern, R. Vandenbosch and K. Wolf)

2. R. Vandenbosch and K.L. Wolf, Sec. 7.3 of this report ((d,pf) Fission).
5. Section 10.7 of this report.
8.5 Hindrance Factors for Beta Decays of Heavy Nuclei

It is customary to classify beta transitions into allowed, first-forbidden, second-forbidden ones etc. according to the spin and parity changes between initial and final nuclear states. The ft-values of beta transitions have proved to be useful in determining forbiddenness of the transitions and accordingly spins and parities of relevant nuclear states. However, discrimination in ft-values between different forbiddennesses is sometimes obscured by the fact that a number of allowed transitions have the ft-values comparable to those of first-forbidden transitions and similarly for higher forbidden ones. The purpose of this paper is to discuss the origin of such hindrance (retardation) phenomena and also point out a characteristic difference between allowed and forbidden transitions.

Our work started from the study of collective levels which absorb a large portion of the sum rule limit for the transition strength. The sum rule can be written as

\[ \sum_f |\langle f | m | 0 \rangle|^2 = \langle 0 | m^+ m | 0 \rangle = |\langle c | m | 0 \rangle|^2, \]

where

\[ |c \rangle = \frac{m | 0 \rangle}{\sqrt{|\langle 0 | m^+ m | 0 \rangle|}}. \]

If \( |c \rangle \) belongs to the complete set \( |f \rangle \), the sum rule is exhausted by one transition, \( |0 \rangle \neq |c \rangle \). Then even if \( |c \rangle \) is not an exact eigenstate and has a finite

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**Fig. 8.5-1.** Beta-transitions on the collective states of Fermi type \( f_1 \) (a), Gamow-Teller type \( f_0 \) (b), and first forbidden \( f_r \) (c).

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**Fig. 8.5-2.** Level scheme of \( \beta \) and \( \gamma \) transitions and the associated collective states in heavy nuclei. The \( \Delta_\beta \) (\( \Delta_\gamma \)) is the collective excitation energy of the collective state \( |\text{Coll} T(T_2)\rangle \).

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width, existence of such a virtual state can cause the hindrance phenomena (see Fig. 8.5-1).

Hindrance phenomena were studied on the basis of schematic models, which are simple extensions of the one proposed by Brown and Bolsterli. It was suggested that knowledge of the giant resonance can be applied to the calculation of hindrance factors for the beta decay matrix element $f_\nu$ (see Fig. 8.5-2). The collective motions which have no analogues in the electromagnetic transitions play important roles for allowed beta transitions, whereas for the forbidden beta transitions the responsible collective modes are rather familiar ones known in the study of the gamma-ray processes. The hindrance factor due to giant resonance effect is roughly estimated to be $F \approx 4$ for the first forbidden beta-decays.

Since the knowledge of $f_\nu$ in beta decays is so scanty, we examined the empirical systematics of $f_{13}$ instead (see Fig. 8.5-3). A characteristic difference between the hindrance expected for allowed and forbidden beta transitions was noted and discussed in terms of the semi-empirical systematics.

A new method of calculation was proposed for the treatment of nuclear matrix elements for forbidden beta decays, which makes use of knowledge of the corresponding electromagnetic transitions. The physical meaning of this method is clearly seen from the schematic models. The merit of this method is that we can easily estimate the core polarization effect leading to a giant resonance. (H. Ejiri, K. Ikeda and J.I. Fujita)

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3. Presently at Department of Physics, University of Tokyo.
4. Presently at Department of Physics, Indiana University.
9. OTHER RESEARCH PROJECTS

9.1 Nuclear Medicine

In order to make quantitative measurements of total body calcium based on the $^{48}$Ca(n,$\gamma$)$^{49}$Ca activation within the skeleton, it is necessary to devise a means of delivering the same fluence of thermal neutrons to all portions of the skeleton. The principal effort this year was directed toward the development of an exposure scheme which would yield the most uniform activation to a given subject. Thermal neutrons were measured by activation of manganese dioxide capsules inserted into bones of cadavers used in the present work. From a systematic study the following exposure scheme has evolved:

a. The subject is placed in a standing position on a turntable within an enclosure of internal dimension .61m x .61m x 2.44m.

b. The walls of the enclosure are 15.3 cm thicknesses of fir plywood except for the .61m x 2.44m front. The moderator in front is adjusted to compensate for variations in body thickness.

c. The subject is faced toward the target box for the first half-exposure, about 30 seconds, monitored by a LiI detector. The cyclotron is turned off, the turntable rotates 180°, and the cyclotron is turned on again for the second half-exposure, automatically corrected for the decay of $^{49}$Ca (8.8 minute half-life).

Using this scheme, a variation of ± 12% was obtained for specific activation in the first cadaver (43.5kg, 1.60m). In the second, larger cadaver (73.5kg, 1.82m) the variation was ± 20%.

Several more cadavers of various shapes and sizes will be studied to devise a systematic scheme of compensating for these differences.

The spectrum of neutrons incident on the subject has been measured with a $^6$Li-semiconductor sandwich detector (ORTEC). The spectrum peaks at 1.5 MeV.

The whole body counter has been modified to provide greater counting efficiency by improving the geometry of the crystal array and to reduce its space requirements by moving the crystals rather than the subject.

(Robert Murano, Wil B. Nelp, and Keith G. Paulthorp)

1 Nuclear Physics Laboratory Annual Report, University of Washington (1967), p. 76.
Optical Double Resonance Studies of 46-min $^{111m}$Cd and 55-min $^{105}$Cd

The success of an earlier experiment on $^{63}$Zn, which has a half-life of 38 minutes, serves as an incentive to undertake experiments on other short-lived isotopes of the Group II elements. As was explained in the previous report, it is desirable to have a high degree of chemical and isotopic purity for samples to be used in optical double resonance experiments. This is most easily achieved with cyclotron-produced isotopes. The new series of experiments deals with $^{105}$Cd and $^{111m}$Cd. The isotopes are produced by the reactions $^{104}$Pd($\alpha$,3n)$^{105}$Cd and $^{110}$Pd($\alpha$,3n)$^{111m}$Cd. A prebaked high purity palladium foil is bombarded with 42 MeV alphas for about 75 minutes at an external beam intensity of 30 μamp. Counting measurements indicate that about $8 \times 10^{12}$ $^{105}$Cd atoms and $3 \times 10^{13}$ $^{111m}$Cd atoms are produced compared with the $3 \times 10^{13}$ $^{105}$Cd and $^{111m}$Cd atoms expected from a mean reaction cross section of 1.5 barn. This estimate is derived from a reaction cross section obtained from the expression $\sigma = \pi(R + \lambda)^2$. $R = 1.4A^{1/3}$ fermi is the strong absorption radius of the target nuclei and $\lambda$ is the radius of the incident $\alpha$. These results imply that $\sigma(111mCd) = 4 \sigma(105Cd) = 1.5$ barn. The isotopes $^{107}$Cd and $^{109}$Cd are also produced in the foil by the reactions $^{106}$Pd($\alpha$,3n)$^{107}$Cd and $^{108}$Pd($\alpha$,3n)$^{109}$Cd. The cadmium activity is quickly distilled from the target by heating it in a carbon crucible under vacuum to $\nu$ 1550°C and is transferred to a quartz resonance cell by further distillation.

The direction and polarization of 3261 Å optical resonance radiation scattered from the sample in the resonance cell can be studied as a function of applied static and rf magnetic fields. The 3261 Å radiation connects the $^2S_0$ ground state and the excited $^3P_1$ state at 3.6 eV. The usual experimental procedure has been to illuminate the sample with unpolarized light directed along the magnetic field and to detect that light scattered at right angles to the field which is linearly polarized parallel to the field. With this arrangement an rf transition between Zeeman sublevels of the $^3P_1$ state results in an increase in the observed light scatter.

A total of three different Zeeman transitions in $^{111m}$Cd were observed in magnetic fields up to 551 gauss. From these observations it is possible to determine the spin and hyperfine interaction constants in the $^3P_1$ state and hence deduce the magnetic dipole and electric quadrupole moments of $^{111m}$Cd. The spin $I = 11/2$ follows from the observation of a Zeeman resonance spec-

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Fig. 9.2-1. Zeeman resonance signals in the $F = 13/2$ and $F = 11/2$ hyperfine levels of the $^5^3P_1$ state in $^{111m}$Cd.
trum centered about a magnetic field corresponding to a g-factor of $g_r = 6/143$. Individual Zeeman resonances in the $F = 13/2$ and $F = 11/2$ hyperfine levels are shown in Fig. 9.2-1. A total of five different Zeeman transitions in $^{105}$Cd were observed in magnetic fields up to 389 gauss. The spin $I = 5/2$ follows from the observation of four resonances symmetric about a magnetic field corresponding to $g_F = 3/7$. The spin determination was corroborated in this case by the presence of substantial quantities of $^{107}$Cd($I = 5/2$) and $^{109}$Cd($I = 5/2$) as mentioned earlier. It is easy to show that with $g(107\text{Cd}) = g(109\text{Cd}) = 4$ the relative numbers of isotopes produced are $N(107\text{Cd}) = 32 N(109\text{Cd})$ for a 75 minute irradiation time and a 60 minute isotope recovery time. There are two reasons for this difference: (a) $^{107}\text{Cd}$ and $^{109}\text{Cd}$ do not decay appreciably during production and recovery, (b) the isotopic abundances of $^{106}\text{Pd}$ and $^{108}\text{Pd}$ relative to $^{104}\text{Pd}$ and $^{110}\text{Pd}$ favor the production of $^{107}\text{Cd}$ and $^{109}\text{Cd}$ by a factor of 2.5.

Individual Zeeman resonances in the $F = 7/2$ and $F = 5/2$ hyperfine levels are shown in Fig. 9.2-2.

Isotopic identification can be made by following the decay of the amplitude of an individual resonance signal. Figure 9.2-3 shows that the decay of the amplitudes of the $(F = 11/2, m_F = 11/2) \leftrightarrow (11/2, 9/2)$ transition in $^{111}\text{Cd}$ and the $(7/2, 7/2) \leftrightarrow (7/2, 5/2)$ transition in $^{105}\text{Cd}$ correspond to half-lives of $47.4$ (1.9) min and $54.0 (1.9)$ min respectively. These are in good agreement with the accepted half-lives of $48.6 (2)$ min for $^{111}\text{Cd}$ and $54.7 (1.3)$ min for $^{105}\text{Cd}$.

A least squares fit of a set of eight $^{111}\text{Cd}$ and nine $^{105}\text{Cd}$ resonance field and frequency measurements to a modified Breit-Rabi Hamiltonian yields the hyperfine interaction constants in the $5\rho_1$ state. The magnetic dipole interaction constants are $A_{111} = -697.1(2)$ MHz and $A_{105} = -1025.9(2)$ MHz. The quadrupole interaction constants are $B_{111} = +202.3(5)$ MHz and $B_{105} = -103.9(3)$ MHz. If these values are compared to those measured for $^{109}\text{Cd}$ in the same atomic state then the values for the nuclear dipole moments $\mu_{111} = -1.104(4) e$ and $\mu_{105} = -0.7384(2) e$ and the quadrupole moments $Q_{111} = -0.85(9) e$ and $Q_{105} = -0.43(4) e$ are obtained. These values are based on $\mu_{109} = 0.62701(20)e$ and $Q_{109} = 0.69(7)$ e.

The spin and dipole moments of $^{105}\text{Cd}$ and $^{111}\text{Cd}$ are consistent with a
Fig. 9.2-3. Decay of the amplitude of the \( (F = 7/2, m_F = 7/2) \leftrightarrow (F = 7/2, m_F = 5/2) \) resonance signal in \( ^{105}\text{Cd} \) and of the \( (F = 11/2, m_F = 11/2) \leftrightarrow (F = 11/2, m_F = 5/2) \) resonance signal in \( ^{113}\text{Cd} \).

Shell model assignment of the neutron ground state as \((2d_{5/2})^5(1g_{7/2})^0(1h_{11/2})^2\) for \( ^{105}\text{Cd} \) and \((2d_{5/2})^5(1g_{7/2})^2(1h_{11/2})^0\) for \( ^{113}\text{Cd} \). The magnitudes of the dipole moment are predicted by the shell model with configuration mixing\(^{4}\) to be \( \mu_{^{105}\text{Cd}} = -0.77 \mu_N \) and \( \mu_{^{113}\text{Cd}} = -1.10 \mu_N \) in good agreement with the measured values. The quadrupole moments of \( ^{105}\text{Cd} \) and \( ^{113}\text{Cd} \) are quite large and are in poor agreement with the predictions of the model used for the dipole moments.
Optical Pumping of $^{107}$Cd and $^{109}$Cd

The high precision measurements of the ratios of the $^{107}$Cd and $^{109}$Cd nuclear magnetic resonance frequencies reported previously have been continued. The isotopes are produced at the cyclotron through the $^{107}$Ag(p,n)$^{107}$Cd and $^{109}$Ag (p,n)$^{109}$Cd reactions in a natural silver target. The final values for the frequency ratios are given in Table 9.2-1.

<table>
<thead>
<tr>
<th>Table 9.2-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_{107}/\nu_{111} = 0.20678100(22)$</td>
</tr>
<tr>
<td>$\nu_{109}/\nu_{111} = 0.27832106(28)$</td>
</tr>
<tr>
<td>$\nu_{107}/\nu_{109} = 0.7429585(5)$</td>
</tr>
<tr>
<td>$\nu_{113}/\nu_{111} = 1.04608417(24)$</td>
</tr>
<tr>
<td>$\nu_{111}/\nu_{11} = 0.2117831(6)$</td>
</tr>
</tbody>
</table>

These results differ little from those reported previously except for the addition of two new results. These are the ratio of the resonance frequencies of $^{113}$Cd to $^{111}$Cd and of $^{111}$Cd to the proton. Both measurements are in good agreement with results reported in other work and are comparable in precision. The measurement of the $^{111}$Cd resonance frequency to that of the proton was carried out by first observing the nuclear magnetic resonance in an optically-pumped sample of $^{113}$Cd and then by observing the resonance frequency of protons in a sample of mineral oil in the same magnetic field. Both samples were contained in identical 3/8 inch diameter spherical cells which could be carefully positioned in the magnetic field. The small size of the samples served to minimize systematic errors traceable to magnetic field inhomogeneities. Problems of this nature had plagued earlier measurements in larger samples.

From the above frequency ratios and the known dipole hyperfine interaction constants for the cadmium isotopes, differential hyperfine structure anomalies have been computed for the valence s-electron in the cadmium isotopes. These are given in Table 9.2-2.

<table>
<thead>
<tr>
<th>Table 9.2-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{107}<em>{111}(s</em>{1/2}) = +.136(4)$</td>
</tr>
<tr>
<td>$^{109}<em>{111}(s</em>{1/2}) = +.130(4)$</td>
</tr>
<tr>
<td>$^{111}<em>{113}(s</em>{1/2}) = +.0010(5)$</td>
</tr>
<tr>
<td>$^{107}<em>{109}(s</em>{1/2}) = +.006(1)$</td>
</tr>
</tbody>
</table>

In the earlier report these experimental values were shown to agree very poorly with those predicted by a shell model with configuration mixing. In that prediction the ground state configurations were those which have usually been assumed for these nuclei. Two recent (d,p) and (d,t) scattering experiments suggest that in cadmium, contrary to what had been previously assumed, the $g7/2$ level is relatively empty while the $h11/2$ level is filled to a considerable extent. With these experiments as a guide, new hyperfine structure anomalies were evaluated for ground state configurations which contained a larger number of $h11/2$ nucleons. Table 9.2-3 compares the predicted values of the hyperfine
structure anomalies computed for the "best" new configurations with the values predicted with the previously assumed configurations.

Table 9.2-3. Values for the differential hyperfine structure anomalies predicted on the basis of the shell model with configuration mixing. The zeroth-order configurations are listed.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Configuration</th>
<th>Hfs Anomalies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>Neutron</td>
<td>107(^\Delta)109 107(^\Delta)111 109(^\Delta)111 111(^\Delta)113</td>
</tr>
<tr>
<td></td>
<td>&quot;old&quot; configurations</td>
<td></td>
</tr>
<tr>
<td>113 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^6(1g(<em>{7/2}))^5(3s(</em>{1/2}))^1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>111 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^6(1g(<em>{7/2}))^6(3s(</em>{1/2}))^1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>109 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^5(1g(_{7/2}))^6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>107 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^5(1g(_{7/2}))^4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;new&quot; configurations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>113 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^5(1g(<em>{7/2}))^2(3s(</em>{1/2}))^1(lh(_{1/2}))^6</td>
<td></td>
<td>+0.09% +0.08% +0.09% +0.12%</td>
</tr>
<tr>
<td>111 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^6(1g(<em>{7/2}))^2(3s(</em>{1/2}))^1(lh(_{1/2}))^4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>109 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^5(1g(<em>{7/2}))^2(lh(</em>{1/2}))^4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>107 (1g(<em>{9/2}))^8 (2d(</em>{5/2}))^5(1g(<em>{7/2}))^0(lh(</em>{1/2}))^4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Although the agreement is not perfect it is very substantially improved. The new configurations are also more satisfying in another way. Namely, they allow the magnetic dipole moments of 107\(^\text{Cd}\), 109\(^\text{Cd}\), 111\(^\text{Cd}\) and 113\(^\text{Cd}\) to be calculated with reasonable values of the single parameter which enters in the theory. Thus within the limitations of the particular configuration mixing model employed, it seems possible to conclude that the measured magnetic hyperfine structure anomalies qualitatively confirm the conclusions of the (d,p) and (d,t) scattering experiments.

This research is supported by National Science Foundation Grants GP 3490 and GP 5436 (N.S. Laulainen, M.N. McDermott, P. Spence, Department of Physics).

10. INSTRUMENTATION FOR RESEARCH

10.1 Installation of 90 cm Broad Range Spectrograph

Work is now in progress to move the 90 cm Brown-Buechner type Magnetic Spectrograph from the cyclotron cave to tandem Cave I. A large gun mount obtained from Navy Surplus and located in Cave I while the building was under construction has been employed to provide a rotating turntable on which the 23 ton magnet is mounted. The 24-in. scattering chamber for the magnet is similar to the general purpose 24-in. chamber described earlier, except that the ports have been omitted and a slot in the wall has been added. The chamber will be rigidly attached to the floor and will not rotate with the spectrograph. Two separate sliding foil assemblies are being constructed, for use with either an internal or an external Faraday cup. The latter is considered important for particle-gamma coincidence experiments using the magnet.

An additional beam line from the switching magnet is being provided for 180° cross section measurements, as indicated in Fig. 10.1-1. This will permit the beam to be bent onto the target by the spectrograph, and the 180° particles

Fig. 10.1-1. Layout of tandem Cave I showing location of spectrograph and turntable and indicating normal and 180°-entry beam lines.
analyzed by the magnet.

Initially, position-sensitive detectors and photographic plates will be used for particle detection. However, the magnification and dispersion of the spectrograph make spark-chamber readout quite feasible, and a system of this type is under study. (J.G. Cramer, D. Cough and J.S. Heagney)


10.2 Identification of Heavy Reaction Products by Time-of-Flight

The spectra of light charged particles emitted during fission have been measured using ΔE-E systems.1,2 An alternate and more favorable method for heavier species (A > 10) is by using a time-of-flight system. Bombardment of 12C with 42 MeV 4He particles from the 60 in. cyclotron provided a good selection of heavy charged particles for checkout of a time-of-flight system. Each beam burst has a 2 nsec width and the separation between bursts is 88 nsec. The charged particles were collected in a large surface-barrier detector, either 4 or 1.5 cm² in area, located 0.63 meters from a 100 μg/cm² carbon target in a 60 in. scattering chamber. Timing signals were obtained from two ORTEC 260 time pickoff units and fed into an ORTEC 405 time-to-pulse height converter; the start signal originated from the detector while the stop signal originated from the attenuated cyclotron RF. The smaller (150 mm²) detector was cooled with a 20 watt thermoelectric device; the cooling lowered the leakage current a factor of five and allowed larger bias thereby decreasing the pulse rise time and allowing more efficient detection of particles of lower energy (<6.0 MeV) by the timing system.

Coincident time and energy information was routed to an SDS 930 computer which acted as a 64 × 64 channel two-parameter analyzer. The entire spectra of charged particles from 4 to 15 MeV was displayed live on a display oscilloscope. The charged particle spectra observed in the two parameter spectrum coincided with the spectra predicted (at 46° laboratory angle) on an isobaric family of curves on a Δt (flight time) vs. E plot. A continuum of 3He, 4He, the ground state and first excited state of 12C, the 6Li ground state plus another 6Li state resulting from the 0.717 MeV 10B excited state were clearly observed. The spectrum for the A = 7 isobars consisted of unresolved states of 7Li and 7Be; some events were expected on the A = 6 isobar at the same energy, but these were not clearly resolved from those on the A = 7 isobar. A small peak on the A = 16 isobar, corresponding to inelastic scattering to the first excited state of 16O, indicated a small 15O impurity in the target of the order of one part per thousand. (C. Rudy and R. Vandenbosch)
10.3 Gamma Detector Efficiency Calibration

The efficiency of a 4-in. diameter by 4-in. long NaI(Tl) gamma ray detector, which is used for proton spin flip\(^1\) and other particle-gamma correlations\(^2\) was remeasured at 4.44 MeV. The original efficiency measurement had been done some years ago, but with improved accuracy in correlation measurements brought about by use of the Van de Graaff rather than the cyclotron, it was felt that a check measurement should be made. Two lead absorber shields are used in configuration with the gamma detectors: one for correlations in the reaction plane, and one for perpendicular (spin flip) correlations. Since both the spectrum shape and the efficiency are dependent upon the shield geometry, measurements were made with each shield.

The use of a calibrated detector for \((\alpha,\alpha'\gamma)\) in-plane correlations permits one to determine the \(m = 0\) substate population as well as the \(m = \pm 2\) population (for \(2^+ \rightarrow 0^+\) transitions). Similarly, for the spin flip measurements, one can find the fractional spin flip and the absolute spin flip cross section.

The technique employed is quite standard. Excitation of the 4.44 MeV level in \(^{12}\text{C}\) by protons, provided a source of gamma rays. A low energy was chosen to minimize background from \(^{16}\text{O}\). Angular distributions of both the inelastically scattered protons, and the de-excitation gamma rays were measured. Integration of the proton distribution gives the total number of de-excitation gammas ejected vs. angle. A coincidence measurement of one pair of angles is used to determine the spectrum shape.

A 200 \(\mu\text{g/cm}^2\) carbon dot 3.1 mm in diameter mounted on a thin gold backing was used for a target. This arrangement localized the source of the gamma radiation to the focus of the shielding configuration, and simulated the beam spot at higher energies.

An excitation function was run over the region of interest in order to choose the optimum proton beam energy for the measurement (see Fig. 10.3-1). From this excitation function, run with a large 197 \(\mu\text{g/cm}^2\) carbon foil, a beam energy of 5.140 \(\pm 0.003\) MeV was chosen.

The measurement of the carbon 4.444 MeV total inelastic cross section was performed by normalizing the data to elastic events monitored at 150° (laboratory angle) with a detector.

\[ \theta_p = 165^\circ (\text{Lab}) \]

\[ 2^+ \text{ First Excited State} \]

\[ 4.444 \text{ MeV} \]

\[ \text{Counts normalized to integrated beam} \]

\[ \text{Target} \]

\[ \text{Thickness} \]

\[ 197 \mu\text{g/cm}^2 \]

\[ \text{Fig. 10.3-1. } ^{12}\text{C}(p,p') \]

Excitation Function.
having a solid angle of $2.282 \times 10^{-4}$ steradians. This monitor counter had a 4.76 mm diameter circular aperture in front of it at a distance of $27.94 \pm 0.013$ cm from the target center.

The inelastic differential cross section was measured from $10^\circ$ to $170^\circ$ in $5^\circ$ steps (laboratory angles) with acceptance angles of $1^\circ$ wide by $2^\circ$ high. At most angles at least $10^4$ inelastic events were observed. The inelastic differential cross section was numerically integrated by several techniques and the total inelastic cross section was found to be $808.86 \pm 0.35\%$ (inelastic events per elastic monitor). The error represents both the statistical error in the data and the maximum deviation in the results of the various numerical integration techniques.

The gamma-ray angular distribution was then measured from $20^\circ$ to $150^\circ$ in $10^\circ$ steps and normalized to the monitor. The gamma angular distribution was corrected in first order for finite solid angle effect, and the data was fitted to a function of the form

$$W(\theta) = A_1 + A_2 \cos^2(\theta) + A_3 \cos^4(\theta)$$

by means of a linear $\chi^2$ computer program. The parameters were then scaled to yield the same total number of gammas as inelastic events. This last step was necessary as only the upper 2 MeV of the gamma spectrum was used to obtain the gamma angular distribution. This was necessitated by low energy background observed in the gamma spectrum.

The data and fit are shown in Fig. 10.3-2, arbitrarily normalized. The appropriate normalization parameters are $A_1 = 31,580.8$, $A_2 = 235.429$, and $A_3 = 228.475$ per elastic monitor event. Error calculations on the gamma ray angular distribution are not complete at this time.

With the above parameters one can now integrate the gamma angular distribution over the geometrical angular width of the gamma counter and obtain, at a prescribed gamma counter angle, the number of gammas ($N_\gamma$) per monitor elastic. The number of observed gammas ($N_\gamma$) are related to $S_\gamma$ by

$$N_\gamma = f \epsilon \Omega S_\gamma$$

where $\epsilon$ is the absolute intrinsic efficiency of the detector, $\Omega$ is the effective solid angle of the detector and shield, and $f$ is the fraction of

---

**Fig. 10.3-2.** Gamma-ray angular distribution; fit and data.
the total gamma spectrum observed (f is usually less than 1 because of an artificial cutoff set by discriminators in the electronics). The number which is useful in the previously mentioned experiments is \( f \). \( f \) is determined from the gamma ray spectrum shape.

The spectrum shape was measured by detecting gammas in coincidence with the \( ^{12}C \) inelastic proton group.

Final calculations are not yet completed; however, preliminary calculations show good agreement with the measurement made on the cyclotron, with the possible exception of the spectrum shape near the low energy end of the gamma spectrum.

It should be pointed out that it is now possible to determine \( f \) for any other counter and shield combination at 4.444 MeV by using the parameters arrived at above in conjunction with a monitor system as described. (J. Eenmaa, T.D. Hayward, R.H. Lewis, D.M. Patterson and J.R. Tesmer)

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1. Section 4.1 of this report (proton spin-flip).
2. Sections 1.2 and 4.2 of this report (\(^{3}He\) spin-flip and \((a,a'\gamma)\) angular correlation).

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10.4 Design and Construction of Electronic Equipment

Projects carried out during the past year include:

a. The construction of ten 15MHz 8-digit scalers has been completed and the units are in operation. The scalers include provisions for direct BCD read-in to the computer, variable paired-pulse resolution, and overflow indication.

b. The readout of the NMR frequency, used to monitor the accelerator beam energy, has been interfaced to the computer.

c. Local audio devices (4) attached to the neutron monitors have been designed and constructed to alert personnel to the building of high neutron radiation levels.

d. A variable oscillator, mixer and count rate meter has been designed and constructed to use with a quartz crystal microbalance in a system to monitor target thicknesses. See Section 10.8 of this report.

e. A unit has been designed and constructed to use in conjunction with the Van de Graaff beam chopper to allow alternate periods of activation and data recording in work with targets of short half-life. The unit permits activation times between 150 nsec and 10 \( \mu \)sec and repetition rates between 1 KHz and 100 KHz.

f. A 3-channel pre-scaler, compatible with AEC standard bins, has been designed and constructed to accommodate the gross differences in counting rates which occur in some multi-counter experiments.

g. A temperature measuring system has been developed to monitor and control the temperature of the potassium cell in the alpha particle ion source. The temperature sensor is a thermistor. The thermistor
voltage is converted into a pulse train which is transformer coupled across a 40-kV potential difference to a readout and control unit (at ground potential).

h. Several power supplies have been constructed for bench checking and repair of plug-in units for AEC standard bins.

i. Five charge-sensitive preamplifiers with compatible time-pickoff units have been constructed for use in the high vacuum of the scattering chamber.

j. The Goulding identifier system constructed here was re-packaged in an AEC compatible double width plug-in. The single channel analyzer unit was modified to provide a true pulse zero setting of both the upper and lower level adjustments and to provide pulses from the upper and lower discriminators and the input strobe as well as the usual window discriminator.

k. The recently purchased Canberra timing single-channel analyzers were modified with new panels to provide front panel coincidence width adjustment and two additional front panel coincidence outputs. Some confusing panel labels were also eliminated.

l. The following additional plug-in units for AEC standard bins have been constructed: 4 biased amplifiers and pulse shapes, 4 triple-coincidence double-anti-coincidence linear gate units, 8 dual delay amplifiers, 4 dual fast pulse amplifiers, 3 preamplifier power supplies and 1 dual cross-over sensing unit.

m. The laboratory signal-cable system has been updated to include RG114 low capacity cable for solid-state detector connections, Super Flex RG56U and RG8U colored jacket cable for 50 Ω impedance commercial fast-timing circuits, and Suprenant 6244 125 Ω cable to replace RG62U patch panel cables where the impedance matching to the long runs of RG63U is critical.

n. The study and design of the accelerator beam stabilization system has continued. See Section 12.5 of this report.

c. Items purchased include the following:

- 2 Tektronix type RM561A oscilloscopes each with 1.3A72 and 1.2A63 plug-in unit,
- 1 Tektronix type 454 oscilloscope,
- 1 Tektronix type RM17 oscilloscope
- 1 Tektronix C-40 oscilloscope camera,
- 1 Hewlett Packard 50 MHz digital counter
- 1 Power Designs 0-3 kV power supply
- 3 AEC bins and power supplies
- 1 Tennelec 100B preamplifier
- 1 Tennelec 130 preamplifier
- 1 ORTEC time-to-pulse height converter
- 2 ORTEC gate and coincidence units
- 2 ORTEC fast discriminators
- 1 ORTEC detector bias controller
- 4 ORTEC delay amplifiers
- 1 ORTEC active filter amplifier
- 2 ORTEC baseline restorers
- 1 70 kilovolt power supply
- 5 Canberra amplifiers
5 Canberra time single channel analyzers
1 dual #096 Northern Scientific ADC's
2 portable AEC 4 bin cabinet and power supplies
2 thermoelectric coolers and power supplies .

10.5 Design of A Gamma Ray Polarimeter

Early in the year it became apparent that the iron of the old polarimeter was of insufficient thickness to measure the circular polarization of the 4.44 MeV carbon gamma-ray under investigation. Examination showed that modification of the old polarimeter would be extremely inefficient; accordingly, design of a new polarimeter was begun.

The new design will be referred to as the Mark II polarimeter while the old polarimeter will be referred to as the Mark I design.

A number of factors were considered in the Mark II design. These include (1) considerations of the gamma-ray angular distribution, (2) minimum data collection time, (3) usefulness as both a high and moderate energy (4.5 to 1.3 MeV) gamma ray polarimeter, and (4) physical limitations imposed by the 60 inch scattering chamber.

If the $z$-axis is defined in the direction of $\mathbf{k}_1 \times \mathbf{k}_f$, where $\mathbf{k}_1$ and $\mathbf{k}_f$ are the incident and outgoing wave vectors associated with a scattering event, then the gamma rays emitted between a $2^+$ excited state and a $0^+$ ground state are circularly polarized along the $z$-axis. If the $2^+$ state is, as in the case of interest, excited by alpha-particle bombardment, then the only magnetic substates which are excited are $m = \pm 2, 0$. Since only $m = \pm 2$ can yield a polarization

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig10.5-1.png}
\caption{Fig. 10.5-1. Quadrupole radiations patterns for $m = \pm 2, 0$. $\theta_1$ and $\theta_2$ are the half angles defining the polarimeter acceptance. Mark II acceptance angles $\theta_1 = 20^\circ$, $\theta_2 = 37.5^\circ$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig10.5-2.png}
\caption{Fig. 10.5-2. The figure illustrates terms used in photon electron scattering cross sections.}
\end{figure}
Table 10.5-1. 

<table>
<thead>
<tr>
<th>$\theta_1$</th>
<th>$\theta_2^{+}$</th>
<th>$\theta_1, \theta_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$15^\circ$</td>
<td>$20^\circ$</td>
</tr>
<tr>
<td>10°</td>
<td>3.01</td>
<td>2.88</td>
</tr>
<tr>
<td>15°</td>
<td>2.82</td>
<td>2.77</td>
</tr>
<tr>
<td>20°</td>
<td>2.76</td>
<td>2.68</td>
</tr>
<tr>
<td>30°</td>
<td>2.64</td>
<td>2.55</td>
</tr>
</tbody>
</table>

we wish to find the angle where the distribution of the radiation (Fig. 10.5-1) favors observation of the m = +2 substates over the m = 0 substate, and yet lies near the z-axis. Table 10.5-1 shows the ratio of intensities $I_0(\theta_1, \theta_2)/I_{+2}(\theta_1, \theta_2)$ between the m = 0 substate and the m = +2 substates in a region defined between two cones of half angle $\theta_1$ and $\theta_2$ lying along the z-axis (see Fig. 10.5-1); it is assumed that the population of the m = 0 substate is equal to the population of the m = +2 plus the m = -2 substates. In addition to minimizing the ratio $I_0(\theta_1, \theta_2)/I_{+2}(\theta_1, \theta_2)$ it is desirable to maintain a solid angle such that the polarimeter transmission is about $10^{-3}$. The circular polarization is a maximum along the z direction and becomes zero in the reaction plane ($\theta = 90^\circ$).

The problem is thus to choose design parameters which will take each of the above factors into consideration and produce a meaningful statistical measurement of the circular polarization in a minimum time of measurement. In order to simplify the calculation, it is assumed that the gamma rays are 100% circularly polarized and that the linear polarization is zero. Then the asymmetry, $\delta$, in counting rate between scattering from electrons with their spins approximately parallel to the incident photon direction, and scattering from electrons with their spins approximately antiparallel to the incident photon direction is given by

$$\delta = 2f P_c \frac{\phi^-}{\phi^0},$$

where $f$ is the fraction of aligned electrons, $P_c$ is the degree of circular polarization, and $\phi^0$ and $\phi^- \phi^0$ are the non-polarization Compton cross section and the circular polarization dependent cross section, respectively. Now the relative amount of time, $\tau_R$, required to measure a statistically significant asymmetry at a fixed counting rate is proportional to $\delta^{-2}$, whereas the length of time to collect counts giving a certain statistical accuracy is proportional to $(\delta_c)^{-1}$. We thus wish to investigate the behavior of the ratio

$$\tau_R \propto \left| \frac{(\phi_0)^2}{(\phi^-)^3} \right|$$

$\phi_0$ and $\phi^-$ are given by
\[ \Phi_0 = 1 + \cos^2(\theta) + (k_0 - k)(1 - \cos \theta) \]
\[ \Phi'_0 = -(1 - \cos \theta)[(k_0 + k)\cos \theta \cos \Psi + k \sin \theta \sin \Psi \cos \theta'] \]

where \( k_0 \) and \( k \) are the incoming and outgoing wave numbers (in units of \( m_0c^2 \)), respectively.

The angles (as shown in Fig. 10.5-2) are: \( \theta \) = photon scattering angle, \( \Psi \) = the angle between the incident photon \( k_0 \) and the electron spin \( \vec{S} \), and \( \theta' \) = the angle between the \( (k_0'\vec{k}) \) plane and the \( (k_0\vec{k}) \) plane. Figs. 10.5-3 and 4 are contour maps for two gamma energies, where \( \tau_R \) is plotted as the elevation versus the angles \( \theta \) and \( \Psi \). In these plots \( \cos \theta' \) has been taken equal to 1. It should be noted that Figs. 10.5-3 and 4 contain the same constant of proportionality; thus \( \tau_R \) is considerably larger for the lower energy gamma rays even at the minimum.

Fig. 10.5-3. Relative time for data collection (\( \tau_R \)) for 4.444 MeV gamma radiation.
The values of $\tau_R$ shown in Figs. 10.5-3 and 4 were calculated by a code written for and run on the SDS 930 computer. Values were calculated at each 5° interval in $\theta$ and $\psi$ over the range $\theta = 0°$ to $180°$ and $\psi = 0°$ to $180°$. The regions marked III and IV represent a back scatter polarimeter ($\theta \sim 180°$). Unfortunately such a polarimeter would be impossible to construct and use in a scattering experiment; therefore, we are forced to construct the polarimeter around the minimum in region I.

Because most gamma rays which would be of interest in measurements of this type lie between 1 and 1.5 MeV, and since the minimum for the lower energy gamma ray (Fig. 10.5-4) is much shallower and steeper walled than for the 1.44 MeV gamma ray, the polarimeter was designed to favor the lower energy.

In order to maintain the proper angle, $\psi$, between the photon direction and the electron spin, the inner wall of the polarimeter was constructed of a

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Fig. 10.5-4. Relative time for data collection ($\tau_R$) for 1.37 MeV gamma-radiation.
series of conical sections, the taper of each of which was chosen to maintain
the angle \( \Psi \) constant (see Fig. 10.5-5). The outer surface of the inner wall
is then tapered in such a way to keep the magnetic flux density in the wall near-
ly uniform. The flux density in the inner wall was chosen to saturate the
iron in order to align the largest fraction of electrons. The cross section
of the return path was chosen such that the flux density corresponds to the
maximum permeability of the iron, and thus the ampere turns required by the
field coil is a minimum.

The shape of the inner wall de-
termines \( \Psi \) but the position of the gamma
detector along the axis of the polarimeter (away from or toward the target)
determines the average scattering angle \( \langle \delta \rangle \).

\( \tau_R \) was also calculated in 1° incre-
cements over region I (see Figs. 10.5-3 and 4). One can then calculate accu-
ately the time efficiency of the de-
sign, which is given by

\[
\epsilon_\tau = \left(1 - \frac{\langle \tau_R \rangle - (\tau_R)_{\text{min}}}{(\tau_R)_{\text{min}}} \right)
\]

\( \Phi / \Phi_0 \) was also calculated over region I
in 1° increments. This makes it pos-
sible to determine \( \Phi / \Phi_0 \) for the de-
sign. Using this number one can then predict the value of \( \langle \delta \rangle \) in a given
experiment if \( P_\gamma \) has been previously
determined, say from an \( (\alpha,\alpha'\gamma) \) angular
correlation. The calculations show
that for 4.444 MeV gamma radiation the
time efficiency of Mark II is 0.86
whereas it is 0.72 for a cylindrical
inner shell. This represents about a
20% reduction in data collection time.

The expected value of \( \langle \delta \rangle \) for
4.44 MeV gamma rays with \( P_\gamma = 1 \) is
0.092. If the circular polarization
of the radiation were along the direction of propagation rather than along the
z-axis, the asymmetry would be 0.109. The maximum possible value is 0.114,
under the ideal choice of angles.

A more detailed description of the theory of compton scattering polarimeters may be found elsewhere.\(^3\)

Construction of Mark II has been completed. Assembly and tests are presently being carried out. (T.D. Hayward)

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1. Section 5.1 of this report (gamma ray polarization measurement).
2. The minus superscript, $\phi_C$, implies the polarization dependent cross section when the electron spin is approximately antiparallel to the incoming photon direction.

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10.5 **High Energy Gamma Ray Detector Improvements**

The number of high energy gamma rays one observes from a nuclear bombarding is extremely small compared to the copious quantities of low energy gammas. Hence, to obtain sufficient statistical information on high energy gamma rays it is necessary to count for long periods of time at high counting rates. Because of this the energy calibration and resolution are very sensitive to shifts in gain throughout the electronic system. The type of phototube used (XP1031) for the central detector (3 in. by 6 in. NaI) in our gamma spectrometer has been found to have large gain shifts when subjected to high counting rates even when the dynode current through the last 4 dynodes is large and well regulated by zener diodes. For example, the gain of one tube increased by 15% in 10 minutes after a discontinuous increase in the counting rate due to a $^{60}$Co source from $\approx$300/sec to $\approx$20,000/sec. Even after 10 minutes it continued to increase its gain at a rate of about 2% per hour. To compensate for such gain shifts a gain stabilization system is being built. It makes use of a light pulser designed to produce large, uniform, nanosecond flashes of light. When tested each flash is hoped to be equivalent to that associated with the photocell of a 30 MeV gamma ray. A computer on-line software stabilizer program is planned to stabilize the storage of the spectrum using the light pulser as a reference. Such a program cannot economically handle count rates of 20,000/sec, so methods for reducing the counting rate of less interesting parts of the spectrum are being explored.

A new lead collimator designed for gas target experiments has been built for the annulus detector. With the collimator and the detector at about 76.2 cm from the target, the field of view seen by the detector is 2.54 cm in diameter whereas an older collimator having the same solid angle had a field of view 30.5 cm in diameter. For gas targets larger than 2.54 cm across it is hoped that background from beam passing through the entrance and exit foils can be minimized by using this collimator.

In addition, a neutron shield of borated paraffin (25% borax - 75% paraffin by weight) has been built to surround the annulus system. It is 12.7 cm thick towards the target to stop fast neutrons and 2.54 cm thick elsewhere. To
minimize the transmission of thermal neutrons. This shield should improve the anticoincidence efficiency of the annulus by lowering the annulus counting rate caused by neutron capture in the NaI of the annulus and in its lead shield. (D. Johnson, I. Halpern and S. Whetstone)

10.7 Large Volume Ge(Li) Detector

It has become clear from experiments performed here with a small Ge(Li) detector that a good large-volume Ge(Li) detector would make possible a number of interesting experiments. A 20 cc coaxial detector has been purchased.\(^1\) A coaxial detector was judged to offer the best compromise between the demands for efficiency, resolution, and fast timing. The resolution at 1.33 MeV was 4.0 keV.

A major problem with the new detector was that any cyclotron experiment must be done in the 60 in. scattering chamber. A cryostat was designed which placed the detector at the end of a 30 in. cold-finger. This cold-finger can be inserted into the chamber through any of the ports which are located every 30° around the chamber.

A simple computer program was written which calculated the two-escape peak efficiency using the pair production cross section for germanium. This program provided an approximate efficiency calibration above 2 MeV, the shape of the calibration curve, and the dependence of the efficiency on source distance. So far the efficiency has been measured at 4.4 and 15 MeV. The calculation over-estimates the efficiency by about 50%.

The Ge(Li) detector was used in a number of experiments (see Secs. 3.9, 5.4 and 8.4) until quite recently it developed a vacuum leak and had to be returned to the manufacturer for repairs. (D. Chamberlin and S. Ferguson)

1. ORTEC, Inc., Oak Ridge, Tennessee.

10.8 Target Preparation

During the past year 180 targets were prepared in the laboratory. Only the targets that differ in material or in fabrication technique from those reported previously\(^1,2,3,4\) have been listed in Table 10.8-1. Some of the more interesting techniques developed will be discussed briefly.

A used Welmatic spot welder Model 1016C was purchased for the fabrication of custom evaporation sources. A Parr Instrument Company pellet press with punch and die sets for making pellets in diameters from 0.3 cm to 1.3 cm was purchased so that powdered metals and compounds may be consolidated to minimize outgassing during evaporation. A Sears, Roebuck and Co. approximately 0.9 cubic meter (31 cu. ft.) upright freezer was purchased to store reactive targets and detectors. A quartz crystal film thickness monitor similar to that described by Lins and Kukuk\(^5\) was built. The 5 MHz quartz crystals were purchased from the

155
<table>
<thead>
<tr>
<th>Target</th>
<th>Form</th>
<th>Method of Preparation</th>
<th>Backing $^a$</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>TiH$_x$</td>
<td>High Temp. sorption</td>
<td>1000-5000 µg/cm$^2$ Ti</td>
<td>--</td>
</tr>
<tr>
<td>$^{6,7}$Li</td>
<td>Metal</td>
<td>Vac. Evap.</td>
<td>50 µg/cm$^2$ Ni</td>
<td>100-200 µg/cm$^2$</td>
</tr>
<tr>
<td>Adenine</td>
<td>Vac. Evap.</td>
<td></td>
<td>20-40 µg/cm$^2$ C</td>
<td>50-1000 µg/cm$^2$</td>
</tr>
<tr>
<td>N</td>
<td>Melamine</td>
<td>Vac. Evap.</td>
<td>100-400 µg/cm$^2$ Au</td>
<td></td>
</tr>
<tr>
<td>$^{25}$Mg</td>
<td>Metal</td>
<td>Vac. Evap.$^b$</td>
<td>S.S.</td>
<td>200 µg/cm$^2$</td>
</tr>
<tr>
<td>P</td>
<td>$P_4S_7$</td>
<td>Vac. Evap.</td>
<td>40 µg/cm$^2$ C</td>
<td>500-750 µg/cm$^2$</td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>Metal</td>
<td>Vac. Evap.$^b$</td>
<td>50 µg/cm$^2$ C</td>
<td>100-400 µg/cm$^2$</td>
</tr>
<tr>
<td>V</td>
<td>Metal</td>
<td>Vac. Evap. (elect. bomb.)</td>
<td>50 µg/cm$^2$ C</td>
<td>100-250 µg/cm$^2$</td>
</tr>
<tr>
<td>Mn</td>
<td>Metal</td>
<td>Vac. Evap.</td>
<td>50 µg/cm$^2$ C</td>
<td>85-150 µg/cm$^2$</td>
</tr>
<tr>
<td>$^{54,56}$Fe</td>
<td>Metal</td>
<td>Vac. Evap. (elect. bomb.) S.S.$^d$ 20-50 µg/cm$^2$ C</td>
<td>100-1000 µg/cm$^2$</td>
<td></td>
</tr>
<tr>
<td>$^{58,60}$Ni</td>
<td>Metal</td>
<td>Vac. Evap. (elect. bomb.) S.S.$^d$ 20-50 µg/cm$^2$ C</td>
<td>100-1000 µg/cm$^2$</td>
<td></td>
</tr>
<tr>
<td>$^{72,73}$Ge</td>
<td>Metal</td>
<td>Vac. Evap. (elect. bomb.)</td>
<td>50 µg/cm$^2$ C</td>
<td>100-1000 µg/cm$^2$</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>RbNO$_3$</td>
<td>Vac. Evap.</td>
<td>50 µg/cm$^2$ C</td>
<td>500 µg/cm$^2$</td>
</tr>
<tr>
<td>Ce</td>
<td>Metal</td>
<td>Vac. Evap.</td>
<td>S.S.</td>
<td>500-2000 µg/cm$^2$</td>
</tr>
<tr>
<td>$^{205}$Tl</td>
<td>Metal</td>
<td>Vac. Evap.</td>
<td>50 µg/cm$^2$</td>
<td>1000 µg/cm$^2$</td>
</tr>
<tr>
<td>$^{204,206,207,208}$Pb</td>
<td>Metal</td>
<td>Vac. Evap.</td>
<td>S.S.</td>
<td>300-2000 µg/cm$^2$</td>
</tr>
</tbody>
</table>

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a. S.S. indicates self-supporting targets.
Sloan Instruments Corporation.

a. Cerium

Self-supporting cerium metal foils 500-2000 µg/cm² have been prepared and kept reasonably free from oxidation for periods of up to six months. The metal is evaporated onto a teepol polished glass slide, stripped from the slide under argon using a high quality, single-edged stainless steel razor blade, mounted and transferred to an argon filled dessicator with dessicant and stored in a freezer at -10 °C.

b. Lead

Isotopic lead metal foils 300-2000 µg/cm² have been prepared with negligible oxygen, carbon and other light element contamination. Lead isotopes available from Oak Ridge National Laboratory as the nitrate must be converted chemically to the oxide and then reduced in hydrogen to metal. The metal is evaporated onto a teepol polished glass slide in a high vacuum ultra clean system. Thus contamination of the lead is kept to a minimum during the evaporation process. The deposit is floated off on deionized water in a container filled with argon and quickly picked up on a frame. Any excess water is removed with an absorbent tissue and a mild stream of argon is passed over the foil to evaporate any residual water. It is crucial that the lead be floated off and picked up as quickly as possible to minimize the amount of oxidation. The target is placed in an argon filled dessicator with dessicant and stored in a freezer at -10 °C.

c. Iron and Nickel

Uniform, pinhole free iron and nickel foils may be made self-supporting over a wide range of thicknesses by evaporating the metal onto the well cleaned bright side of a piece of 3 micron thick copper⁶ and the copper etched away. The resulting foil is washed thoroughly by repeated flotation in deionized water, picked up on a frame and mounted. Thicker foils must be vacuum annealed before stripping off the copper.

d. Tin and Zinc

Isotopic tin and zinc metal targets are prepared self-supporting starting with the oxide. The oxide is reduced to metal electrolytically and the metal evaporated onto a glass plate well polished with teepol detergent. A tantalum tube boat 3 mm diameter by 25 mm long with a 0.5 mm pinhole opening is used in order to obtain a high vapor intensity. With the receiver placed 1.3 cm from the boat and using 5 mg of metal, a 400 µg/cm² deposit may be obtained. The deposit is removed from the slide by scraping with a high quality, single-edged stainless steel razor blade or by floating it off on deionized water. (J. Sauer)
10.9 Manufacture of Silicon Semiconductor Detectors

Lithium-drifted silicon detectors for use in the laboratory continue to be made, essentially according to the method of Lothrop and Smith.1 They range in thickness from 0.5 to 3.5 mm with areas up to 250 mm². Also narrow rectangular detectors with areas 5 × 17 mm have been made. Several can be mounted side by side for use in angular distribution studies.

It has been found that the behavior of both new and used 1 and 2 mm detectors can be improved by heating them overnight at 80 °C under a reverse bias of 500 volts. This usually decreases the noise, permitting the use of higher biases and thereby improving charge collection.

Fig. 10.9-1 is a spectrum of 16.475 MeV protons scattered from a 0.5 mg/cm² 208Pb target. It was obtained using detector number 90 which is 2 mm thick and has an area of 100 mm². The detector was cooled with a thermoelectric cooler to about -15 °C, and a bias of 300 volts was applied. Resolution of 26 keV was obtained as shown by the peaks at 10.47 and 11.78 MeV corresponding to the 6.000 and 4.692 MeV states in 208Pb. (J. Heagney and S. Kellenberger)

10.10 Germanium Detector Production

Following a recent (October, 1967) surge of interest in high resolution gamma ray spectroscopy during accelerator runs, a decision to attempt to produce Ge(Li) detectors here, was made. To date, two detectors have been started. One (of poor quality germanium) is still in the drift process. The other has finished drifting and is now being prepared for use. Preliminary spectra are encouraging and it is hoped that it will become a useful device shortly.

These detectors are being made by a procedure most similar to that of Jamini.\(^1\) This is an A.C. drift procedure which allows observation of the detector status during drift by observation of the current wave form. The germanium is vertical-grown, gallium-doped single crystals obtained from N.P.C. Metals and Chemicals Corporation, (Hoiboken). Cryostats for these detectors are being built at this laboratory and are similar in design to those of Sher.\(^2\) (J. Haagney)

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11. COMPUTER SYSTEM IMPROVEMENTS AND PROGRAMMING

11.1 Computer System Improvements

Major changes in the computer system have included doubling of the memory capacity from 8K to 16K words, and construction and installation of a photoelectric card reader. These are discussed in Sections 11.2 and 11.3 which follow.

Several other improvements have also been incorporated into the system:

a. A new Northern Scientific Model NS-625 dual 4096 channel analog-to-digital converter has been added, bringing to 6 the number of A/D inputs.

b. A new controller has been added to the multiplexer, which makes possible control of the computer from either counting room, control of counting room scalers and analyzer from the computer, either manually or under program control, and independent control of selected ADC's, scalers, etc. by two separate experiments at once.

c. The analyzing magnet NMR frequency meter on the tandem console has been connected to a scaler-read terminal so that it can be read-in by the computer. This makes possible direct determination of the tandem beam-energy by the computer.
(N.R. Cheney, J.G. Cramer, W.K. Dawson, and H. Fauska)

11.2 Computer Memory Expansion

The 8K word core memory originally delivered with the computer main frame has been replaced by a 16K memory purchased from the Fabri-Tek Corporation. We have also purchased the necessary components (transistors, diodes, etc.) and constructed the computer circuit modules required to operate the 16K core-stack. These modules included 10 Inhibit Drivers, 2 Drive Switches, 1 Address Module, and 1 Drive Line Termination Module. Building the modules ourselves resulted in a saving of over 70% of the cost of purchasing them from the computer manufacturer. The overall expansion was accomplished for approximately 55% of the price quoted by the manufacturer.

The necessary computer circuit modules are being fabricated to enable the original 8K stack to be used and give the computer a total memory capacity of 24K words. Several unique computer-related applications are also being considered for this 8K memory.
(J.G. Cramer, N.R. Cheney, W.K. Dawson, and P.B. Stanton)

11.3 Card Reader Construction

Work has progressed on the photoelectric card reader which has been under construction for the past year to the point that it is now used on-line. Several changes are being considered to improve the reader's performance, including a new
Fig. 11.3-1. Side view of Card Reader

picker knife clutch that would increase the reading rate from the present 120 cards per minute to 300.

Initial experience with the new reader has shown it to be very reliable and trouble-free, in contrast to the old electromechanical SDS reader which has been the weak point in the system since its delivery.
(N.R. Cheney, B.L. Scott, P.B. Stanton, and N.G. Ward)

11.4 General Computer Software

Modifications to standard SDS systems

a. The Real Time Fortran magnetic tape BACKSPACE routine was corrected to overcome faulty operation when backspacing binary records.

b. Modifications were made to the Real Time Fortran binary magnetic tape routines in order to make the format used the same as that used by the Standard Fortran system. Analysis of data collected and written on magnetic tape by a Real Time Fortran program can now be carried out using the faster and more efficient Standard Fortran system. (W.K. Dawson)
11.5 Three Body Final State Kinematics Program

A fully relativistic kinematics program has been written for a three body final state in which two of the particles are detected. It uses as input parameters the masses of the incident, target, and two detected particles, the Q value for the reaction, the incident kinetic energy, and the angles (polar and azimuthal) of the two detectors. The program then calculates the third final state particle's mass from the other mass and Q value data. There is one remaining independent variable, which is taken to be the energy of one of the detected particles. The program determines the allowed range of this energy by a search. The output consists of the energy of the other detected particle and the energy and angular coordinates of the third (undetected) particle, given as a function of the energy of the first detected particle. There are at most two solutions to the equations for each value of the first detected particle's energy. Both solutions are given when they exist.

In addition, the program can calculate partial derivatives of each of the four dependent variables with respect to the angles of the two detected particles and with respect to the energy of the first detected particle. Also a modification of the program has been written that displays on the computer CRT a plot of the energy of one detected particle versus that of the other. Such plots can be simultaneously displayed for various sets of angles or various reactions, to help in understanding the effects of detector aperture size and of impurities on the two parameter spectra. (D.W. Storm)

11.6 Optical Model Analysis of Elastic Scattering

Three programs have been written for analyzing elastic scattering data for projectiles with spins 0, 1/2, and 1, respectively. These programs predict elastic scattering cross-sections, phase shifts (S-Matrix), and polarization within the framework of the spin-dependent optical model. These codes were written to take advantage of special SDS 930 computer input-output peripherals, i.e., digit switches, Nixie readouts, CRT display, etc. Separate programs were written for each projectile spin to increase the speed of calculation and to decrease demands on the rather limited memory.

Several reasons motivated the writing of these codes:

a. Spin-orbit DWBA programs have become generally available in the last few years. This has increased the need for good optical-model parameters for both incoming and outgoing channels. The increasing availability of high quality elastic scattering data allows the determination of optical parameters for a variety of energies and projectiles.

b. Much work remains in testing spin-dependent potentials used in the description of direct reactions. The following is an example of a search strategy for determining spin-orbit potentials for a particular reaction. At each of several fixed values of spin-orbit optical-model potential a search can be made among the remaining parameters (in a given region) for the best fit to the elastic data. Each value of this potential (and its respective parameters) can then
be used to carry out DWBA calculations on a larger computer to determine what value of this potential best represents the reaction data.

c. The recent acquisition of a model 930 SDS computer makes large-scale optical calculations both convenient and financially feasible. This computer has several outstanding advantages, the most important being a CRT visual display system which can display data and fit following any optical model calculation.

Two-dimensional displays are made simultaneously of theoretical calculations and elastic data, the data points being made more intense. Polaroid pictures (see Fig. 11.6.1) can be made of any particularly interesting result. Line printer output is optional and can be selected by sense switch settings. Since optical parameters are most often varied between different calculations, these are given to the computer through several digit switches on the computer console. These switches allow alteration of the parameters more easily than cards or teletype input. During a single calculation or during an automatic search, optical parameters (and if desired, χ) are displayed by the computer on a nixie readout panel. At any point in the calculations an automatic search subroutine may be put in control of parameter selection.

These convenient input-output features allow the user to make a series of gross changes in the parameters and examine the effect on the fit. Besides providing much physical insight, these features also allow quick convergence to a reasonable set of parameters with which to initiate an automatic search.

The language of these codes is predominantly SDS FORTRAN II with several special routines written in the SDS assembly language, SYMBOL. Most of the input and output statements require equipment and routines which are not generally available with other computer systems. (W.J. Braithwaite)

Fig. 11.6.1. A simultaneous CRT display of elastic cross-section data and theoretical predictions.

11.7 A Program for On-Line Collection and Analysis of Ge(Li) Gamma-Ray Spectra

A program has been written which allows the SDS 930 computer to be used to collect and analyze gamma-ray spectra from a lithium-drifted germanium detector. The first part of the program is the standard analyzer program modified to accept data from a 2048 channel ADC. A live CRT display of the spectrum allows the experimenter to find peaks as the data accumulates. The first and last channels of each peak are entered from the digit switches. The portion of the spectrum be-
tween the two channels entered is intensified on the CRT display enabling the experimenter to locate the peaks exactly.

The second part of the program performs the data analysis. Each peak in turn is fitted to a Gaussian peak on a straight line background; i.e., the spectrum in the vicinity of each peak is assumed to have the functional form $B + CI + 0.939 A/W \exp\left(-2.77(I-I_0/W)^2\right)$, where $I$ is the channel number, and a search is made for the values of the parameters $B, C, A, W,$ and $I_0$ which give a least square fit to the data. The first guess for the center of the peak, $I_0$, is the axis of a parabola which fits the three highest points in the peak. The first guesses for $B$ and $C$ are the intercept and slope of a straight line drawn from the first to the last channel of the peak. The first guess for the peak area, $A$, is the difference between this straight line and the data. The width, $W$, is calculated by the formula $W = (W_4^2 + I_0W_5^2)^{1/2}$. This formula was derived by assuming that there are two sources of the peak width, (electronic noise which is independent of gamma energy, and statistical fluctuations in the number of electron-hole pairs which depends on the square root of the gamma energy) and that these two sources add quadratically. At the experimenter's discretion the width may be held fixed or varied by the search program. If peaks are closely spaced the program may decide to fit a peak as a member of a doublet or a triplet.

Along with the results of the fit the program prints the statistical error in the peak area, $\chi$, the peak energy, and the approximate background under the peak. The peak energy is calculated assuming a linear energy calibration. Then the spectrum is plotted on the line printer. The width parameters, calibration parameters, and plot controls are entered from the teletype.

The validity of this fitting routine was tested by adding a peak of known area to a spectrum at various points. It was found that due to small fluctuations in the background the initial guess at the area of a 5,000 count peak could vary from 3,000 to 8,000 counts. But the fitting almost always returned the true peak area to within one standard deviation. Additional tests of this kind are being conducted to determine whether the peak width should or should not be varied during the fitting.

The SDS computer memory was recently expanded to 16K words. This allowed the program to be modified to accept data from two 4096 ADC's or four 2048 ADC's. (S.M. Ferguson)

11.8 New Programs

a. FORTRAN Memory Save routines were written to speed up and facilitate the loading of both Standard and Real Time FORTRAN programs. These self-loading card programs dump the FORTRAN main line program plus all subroutines as well as run-time and/or common if desired onto magnetic tape or cards. Each magnetic tape dump is preceded by a bootstrap loader and followed by a file mark. Provided sufficient room is available in erasable store, as is usually the case, the Memory Save programs do not alter the FORTRAN program being dumped. When erasable store is not large enough for the dump routine the loading region can be selected so as to overwrite a region of core not being dumped, e.g., common or
run-time. A magnetic tape positioning program compatible with any FORTRAN pro-
gram in core was written in order to allow the formation of magnetic tapes con-
taining dumps of many FORTRAN programs.

d. SDS supplies a FORTRAN linking system which allows the selective load-
ing and execution of segments of Standard FORTRAN programs under program control. Information is transmitted from one segment to the next through common. This linking system can only be used for Standard FORTRAN. To overcome this restric-
tion as well as to simplify the linking procedure Standard and Real Time FORTRAN
versions of a Symbol subroutine, CHAIN, were written. When a CALL CHAIN(N) is
encountered in the program being executed, the magnetic tape containing the dumps
of both Standard and Real Time FORTRAN programs is rewound and spaced forward to
the Nth file which is then loaded and execution started. Thus Standard and Real
Time FORTRAN programs can now be linked facilitating the preliminary analysis of
data between runs.

c. A call to subroutine UFILE(N,M,IERR) spaces magnetic tape unit N for-
ward if M positive, backward if M negative, over one file mark. The routine sets
IERR to zero if it was successful, to +1 if the end of tape was encountered, and
to -1 if the load point marker was encountered. Since tape motion does not stop
and start for each physical record (as it would if the usual FORTRAN method of
spacing was used) the searching of a data tape for a specific run is speeded up
and the integrity of the data tape is conserved for a longer period of use.

d. A general weighted non-linear least squares fitting program has been
written. Since the reading of the input data, computation of the function, and
plot of original and calculated values are all carried out in subroutines, it is
simple to adapt the program to many uses. Selected parameters can be held fixed
while the search is carried out over others. The program computes both the var-
iance and the correlations of the parameters and appears to be stable when the
search is carried out over as many as 30 parameters. To date versions of the
program have been used for fitting elastic and inelastic cross sections, charged
particle and gamma ray spectra, and angular distributions. (W.K. Dawson)
12. ACCELERATOR RESEARCH AND DEVELOPMENT

12.1 Tandem Operation

Operation of the two-stage tandem accelerator was generally very good throughout the year. A good deal of experience was gained, and our maintenance now is far superior to that of the previous year, chiefly because we are much more skillful at recognizing troubles before they become too serious. For example, at the slightest change in the pattern of terminal voltage fluctuations, as observed on the monitor oscilloscope connected to the terminal pickup "mushrooms", we suspect screen or resistor troubles. In a routine manner we also now record photographically an oscillogram of the terminal current fluctuations by means of the terminal shorting rod. Generally speaking we find 1000 to 1500 hours between pump outs a maximum.

Two new tube sections (Nos. 2 and 3) of the Mark I type were purchased last summer (1967) when it became apparent that the peak operational voltage was gradually declining. Although this trend has continued at a somewhat reduced rate, three factors have made us decide to operate with the original tubes, which are the Mark II type, as long as possible: (a) The Mark I style will require terminal steering for proper acceleration of oxygen beams. Several researches with 0 beams are now in progress. Although steering plates have recently been installed, the system is as yet untested, especially as to its reliability. (b) With the installation of foil stripping (see Sec. 12.8) and the accompanying reduction in loading effects, the terminal is capable of holding higher potentials. (c) (c) With the successful operation of the injector stage (see below) research demands up to 22 MeV are easily satisfied without forcing the tandem.

The Mark II (original) tubes have now passed 13,000 hours of operation. With care, the terminal can be pushed up to 8 MeV, but only with a foil stripper. For some applications a gas stripper is preferable (see Sec. 12.8). Nevertheless we plan to continue with the Mark II tubes as long as possible.

In October the injector stage was officially accepted. This date also marked a return to full day-time operation of the tandem, for personnel no longer had to be in the accelerator tunnel. Use of the injector has grown steadily. Its operation thus far has been remarkably trouble-free and reliable, although we have adopted a policy of gentle handling. Typically, it is operated at 5-6 MV and at 0.8 μA H⁻ (and occasionally D⁻).

The corona "de-ripple" system on the injector is unsatisfactory. The corona screens wear out at an inordinately rapid rate. Despite this lack, the tandem stage regulator is able to take up the slack, and we get along quite well without any corona stabilization. However, there are good reasons for desiring the corona system, and we expect to attack the problem soon.

The number of hours of operation for the injector now totals about 1600. So far we have no evidence of deterioration of either the neutral or accelerator tubes.
The tandem Van de Graaff (FN-3) tank has been opened 9 times in the last year for the following reasons:

1. 5-2-67 - To remove belt, resistors and associated pieces for thorough cleaning; grease drive motor and alternator; belt not changed.

2. 6-1-67 - To install stripper foil wheel and to change screens.

3. 7-25-67 - To change corona needles.

4. 10-30-67 - To replace stripper gas needle valve and install new set of stripper foils; install air lock for corona needle assembly; replace collector screen and up-charge screen.

5. 10-31-67 - To repair broken wire to up-charge screen.

6. 12-21-67 - To grease drive motor and alternator.

7. 3-4-68 - To replace open resistor in H.E. column.

8. 3-19-68 - To put in new stripper foils; install terminal steering.

9. 3-22-68 - To fix leak in kovar seals to terminal steering voltage in stripper box.

The Van de Graaff injector (FN-5) tank has been opened once since acceptance for the following reason:

1-16-68 - To investigate cause of poor beam stability; change up-charge, down-charge and collector screens; tighten strings to adder gas control; install microphone to enable us to hear tank sparks in control room. Troubles were cured.
Table 12.1-1 summarizes the statistics of Van de Graaff operation during the period from April 16, 1967 to April 15, 1968.  
(J.W. Orth, G.J. Rohrbaugh, and F.H. Schmidt)

Table 12.1-1. Statistics of Van de Graaff Operation (2 Stage and 3 Stage Combined) During the Period from April 16, 1967 to April 15, 1968.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (hrs.)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Operation: Research</td>
<td>4739</td>
<td>79.0</td>
</tr>
<tr>
<td>Machine &amp; Component Tests</td>
<td>95</td>
<td>1.0</td>
</tr>
<tr>
<td>Scheduled repairs, modifications, &amp; maintenance</td>
<td>595</td>
<td>10.0</td>
</tr>
<tr>
<td>Unscheduled repairs (incl. going into tanks)</td>
<td>322</td>
<td>6.0</td>
</tr>
<tr>
<td>Experimenter's set-up time</td>
<td>262</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6014</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

Division of Beam Time Among Projectiles:

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Time (hrs.)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>2619</td>
<td>69.0</td>
</tr>
<tr>
<td>$^4$He</td>
<td>198</td>
<td>5.0</td>
</tr>
<tr>
<td>Deuterons</td>
<td>629</td>
<td>15.0</td>
</tr>
<tr>
<td>$^3$H</td>
<td>281</td>
<td>5.0</td>
</tr>
<tr>
<td>$^3$He</td>
<td>153</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4080</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

All use of the Van de Graaff was by Nuclear Physics Laboratory Personnel

12.2 Cyclotron Operations

During the last year the 60-in. cyclotron has operated much the same as in the previous year. No new modifications have been undertaken. The only major repairs have been the replacement of all rubber hoses on the dee stems, and the renewal of the target gate clamping system.

The use of the cyclotron has been distributed between several users outside the University, users within the University but not associated with the Nuclear Physics Laboratory, and "inside" users. The division of time among these users is detailed in Table 12.2-1.  
(J.W. Orth, J.S. Heagney, and L.L. Stumpf)
Table 12.2-1. Statistics of Cyclotron Operation During the Period from April 16, 1967 to April 15, 1968

Division of Cyclotron Time Among Activities:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (hrs.)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operation</td>
<td>1079.9</td>
<td>52.0</td>
</tr>
<tr>
<td>Experimental set-up</td>
<td>410.8</td>
<td>20.3</td>
</tr>
<tr>
<td>Cyclotron testing</td>
<td>147.7</td>
<td>7.2</td>
</tr>
<tr>
<td>Scheduled repairs</td>
<td>116.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Unscheduled repairs</td>
<td>122.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Unsatisfactory operation</td>
<td>123.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Unrequested time</td>
<td>49.1</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2045.8</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

Division of Normal Operation Among Projectiles:

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Time (hrs.)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha Particles</td>
<td>985.1</td>
<td>91.5</td>
</tr>
<tr>
<td>Protons</td>
<td>10.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Deuterons</td>
<td>79.2</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1079.9</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

Bombardments for Outside Users:

- University of Washington
  - Department of Physics - Prof. McDermott
  - Department of Nuclear Medicine
  - Western Washington State College
  - Atomics International
  - University of Oregon
  - Oregon State University
  - Simon Fraser University

<table>
<thead>
<tr>
<th>Institution</th>
<th>Time (hrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Washington</td>
<td>69.2</td>
</tr>
<tr>
<td>Department of Physics - Prof. McDermott</td>
<td>416.0</td>
</tr>
<tr>
<td>Department of Nuclear Medicine</td>
<td>11.4</td>
</tr>
<tr>
<td>Western Washington State College</td>
<td>197.7</td>
</tr>
<tr>
<td>Atomics International</td>
<td>4.0</td>
</tr>
<tr>
<td>University of Oregon</td>
<td>49.7</td>
</tr>
<tr>
<td>Oregon State University</td>
<td>6.0</td>
</tr>
<tr>
<td>Simon Fraser University</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>757.0</strong></td>
</tr>
</tbody>
</table>

12.3 Tandem Stage (FN-3) Improvements

A number of improvements have been incorporated in the tandem stage machine:

a. A new valve was added to the tandem corona head to enable the points to be changed without depressurizing the tank.

b. The "image" control slits, which lie at the focus of the analyzing magnet, were changed from their position directly opposite one another to a staggered position with one slit 8 in. upstream from the other. The purpose is to reduce secondary electrons scattered from one slit from affecting the current to the other. In addition, the support of this section of beam tube was
changed to an overhead structure to eliminate vibration from the mechanical pump mounted on below the tube.

These changes, together with installation of "back-to-back" logarithmic diodes in the slit pre-amplifier input circuit have brought about a marked improvement in the energy regulation of the high potential of the terminal of the tandem.

c. A bank of ten reserve gas storage cylinders was reconnected to the gas handling system and filled with CO₂. The CO₂ is used as a compensating gas to correct for the pure nitrogen added from the nitrogen scavenging system.¹

d. A residual gas analyzer was purchased. A number of residual gas spectra have been recorded to facilitate specialized leak detection. With this instrument leaks can be identified as to whether they are air, water, tank gas, etc.

e. The quadrupole lens at the high energy output of the tandem and those on the various experimental lines have each been equipped with biasing resistors to provide steering² in both the horizontal and vertical directions. Beam adjustment and alignment is greatly facilitated by this type of steering. Its action is very rapid, and once set for one energy requires only a very small adjustment when the energy of the machine is altered.

f. Two Tektronix oscilloscopes with 2-3A72 and 2-2A63 plug-ins were installed to replace the Analab oscilloscopes provided by HVEC to monitor the beam scanners. The previous oscilloscopes had a lack of cooling, which was the cause of high maintenance problems.

(H. Fauska, J.W. Orth, G.J. Rohrbaugh, and F.H. Schmidt)

1 Nuclear Physics Laboratory Annual Report, University of Washington (1967), p. 94.

12.4 Injector Stage (FN-5) Acceptance and Improvements

Beam tests of the injector stage were begun in April 1967 and continued throughout the summer. However, the injector did not meet specifications until late in October. The chief reason for the long delay was failure to obtain the necessary 10⁻⁷ torr vacuum in the accelerating tubes. Many abortive attempts were made to find the leaks by blanking off various sections of beam tubes. Since the leaks were small and did not show up until the tank was pressurized, this became a frustrating and time-consuming task. Finally, the tubes were all dismantled, their vacuum gasket surfaces polished and reassembled, and a sufficiently good vacuum was obtained.

On October 13 the machine ran three-stage operation at 23.6 MeV at 0.6 µa, thus exceeding total design specifications by 2.6 MeV and 0.1 µa. The injector itself operated at 7.0 MV, or 0.5 MW above specifications. However, its performance fell short of specifications at the low energy range (0.5 µa at 4 MV).
The High Voltage Engineering Corporation believed they could meet the low energy performance specifications by returning the Focus I power supply to a negative reference voltage. However, this would be obtained at the expense of the bonus 0.5 MW at the high voltage range. It was felt that this would not be to the Laboratory's best advantage. Consequently, on October 17 the machine was accepted, subject to suitable compensation for inoperative liquid nitrogen automatic trap fillers, a poorly engineered barium-pump furnace, and faulty micro-positioners. Mutually acceptable conditions were met, and all contractual arrangements with HVEC were completed shortly thereafter.

After acceptance several modifications to the injector stage were, or will be, made:

a. An inadequate personnel safety cage around the negative ion source was rebuilt to provide a more reasonable safety factor. The cage was equipped with an automatic grounding system that shorted out all high voltages as well as turning them off whenever a door is opened.

b. The reliability of the automatic liquid nitrogen sensors was improved by replacing the top sensors with a pre-set time delay relay.

c. A vacuum insulated liquid nitrogen filling line was purchased and will shortly be installed in order to reduce losses.

d. A quartz beam viewer situated between the injector and the tandem was motorized, remotely metered, and controlled from the console to facilitate tuning.

e. A lucite rod control system, similar to that installed on the Tandem stage, has been designed and constructed to actuate the various power supplies and valves at the injector terminal. This system will replace the string system now used. The latter has proved to be unreliable and inadequate.

f. The barium pump furnace has been rebuilt in a satisfactory manner by using an Alundum core. (J.W. Orth and G.J. Rohrbaugh)

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2 Manufactured by the Norton Company.

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12.5 *Vertical Plane Beam Position Instability on the Tandem Van de Graaff*

The beam leaving the tandem Van de Graaff accelerator moves in the vertical plane with a "jittering" pattern closely correlated with the voltage fluc-
tations observed at the terminal. Both the terminal voltage fluctuations and
the vertical movement show a pattern which repeats faithfully every belt cycle
(See Fig. 12.5-1) and shows one major peak and a number of smaller ones per cycle
(~ 120 milliseconds). The source of these peaks appears to be related to the
cure pattern of the belt. The mechanism at work here is not completely under-
stood. Some portions of the pattern seem to "wear out" and disappear, while
other characteristics appear to "wear in" and become more pronounced. Installa-
tion of a new type belt with twice (2×) the number of cure sections resulted in a
pattern with primary and secondary minor peaks totaling approximately 30 when
newly installed, but which rapidly (in a matter of about a month) changed to a
pattern similar in character to that of an original type belt, distinctly showing
a "17-peak" variation.

The observed beam motion and terminal voltage fluctuations are due to un-
even charge distribution on the belt. This has been demonstrated by shorting
the terminal to ground through a 10K resistor and at the last plate of the ac-
celerator tube (Fig. 12.5-2). The fluctuations at these two points show the
familiar characteristics of the belt cycle, conclusive evidence of AC coupling
between the belt and the accelerator tube and thus that even perfect voltage
regulation could not eliminate the vertical fluctuations of the beam. It is
significant that this test also shows that a biased stripper type of energy regu-
lator also would not remove these vertical fluctuations.

(N.J. Caling, H. Fauska, F.H. Schmidt)

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Fig. 12.5-1. Vertical Fluctuation Pattern. (a) Vertical beam fluctuation at object
slits. (b) Terminal voltage fluctuation. Time scale 100 millisecond/Division.

Fig. 12.5-2. Belt charge distribution effect on beam. (a) Current from highest
energy plane of accelerator tube when
grounded through 100K ohms. (Scale .2μA/
Division). (b) Current from terminal when
terminal grounded through 10K ohms
(Scale 20 μA/Division). Time scale 100
millisecond/Division.

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12.6 Vertical Plane Beam "Jitter" Suppressor

Vertical jitter of the beam leaving the tandem Van de Graaff accelerator reduces the percentage of beam transmitted to the target and enlarges effective beam spot.

In an effort to enhance machine performance, a control loop has been designed to suppress the vertical jitter of the beam. Since the jitter is imposed on the beam at the accelerator tube by the belt characteristics (see Sec. 12.5) no amount of voltage regulation at the terminal can eliminate the problem. Therefore a system for reducing the jitter by sensing the beam with the vertical object slits, amplifying the signal, taking the difference, and applying a correcting potential across the high energy deflection plates has been devised (Fig. 12.6-1). These plates are no longer used for static beam deflection. Static vertical beam adjustment is now achieved by biasing the high energy quadrupole magnet.

![Block Diagram](image)

**Fig. 12.6-1. Block Diagram -- Vertical plane beam jitter suppressor system for the tandem Van de Graaff accelerator.**

The suppressor system is not completed but preliminary tests indicate a reduction of the vertical jitter by a factor of two (Fig. 12.6-2) which should be further improved by increased gain in the control loop.

Once the amplifiers have been calibrated in terms of slit current and an
optimum gain achieved, a series of tests will be run to determine the control loop's effect on transmission efficiency and on the on-target beam stability.
(N.J. Caling, H. Fauska, F.H. Schmidt)


12.7 Helium Ion Source for the Tandem Van de Graaff

During the last year, work has continued in efforts to produce larger He\(^+\) beams for injection into the tandem Van de Graaff accelerator.

The principal interest in such beams (\(^3\)He\(^+\) and \(^4\)He\(^+\)) was generated by the gamma-ray polarization measurements\(^{1}\) and the \(^3\)He spin-flip measurements\(^{2}\).

The work reported earlier\(^{3}\) was concerned primarily with modifications to the High Voltage Engineering Corporation (HVEC) negative ion source. However, continual deterioration of the HVEC source \(^-\) output (indicating source deterioration) and reports of progress with alkali-metal exchange sources\(^{4,5,6}\) prompted us to fabricate a new source.

The new source has been designed with ease of modification as the prime criterion. This has been accomplished by the construction of a number of insulated electrode supports on which various electrode designs and configurations can be mounted. The electrode supports are mounted on an optical-type bench along which they can be moved as desired to alter electrode spacings, and to which the supports can be clamped (details are shown in Figs. 12.7-1, -2, and -3).

The design also facilitates fabrication, as parts are duplicated for each support. The major electrode configuration modifications from the HVEC ion source have been:

a. a longer, stepped exchange canal;
b. an exchange-canal heater;
c. complete insulator shielding;
d. a source of alkali vapor;
e. cooled electrodes at the ends of the exchange canal to condense alkali metal vapors;
f. a cooled focus electrode;
g. a modified extraction electrode.
An explanation of the reasons for these modifications and their effects are listed below:

a. The longer exchange canal was employed as a means of reducing the alkali metal consumption, which results from the lower pumping speed of the exchange canal and the slightly reduced vapor pressure of the exchange medium. Preliminary measurements of potassium consumption indicated a use of about 22 mg/hr as opposed to about 30 mg/hr for other similar sources.

b. The exchange canal is heated by a nichrome heater wound on a boron nitride sleeve surrounding the exchange canal. The heater is then placed inside a second boron nitride sleeve which is shielded on the outside by a thin stainless steel tube. The exchange-canal temperature is operated between 230°C and 250°C and monitored with a bimetal oven-type thermometer attached to the side of the canal and observed through a port on the side of the ion source box. The purpose of the heater is to prevent potassium which enters the exchange canal from condensing on the inside of the canal.

c. The insulators on the electrode supports have been protected by completely overlapping cylindrical stainless steel shields. These shields were included after noting visually that the insulators on the HVEC source seem to be-
Fig. 12.7-2. Side view of new He⁺ ion source. (1) Duoplasmotron aperture plate (2) source mounting plate (3) extraction electrode (4) focus electrode (5), (12) cooled and baffled electrodes at ends of exchange canal (6) exchange canal (7) alkaline metal cell heater (8) alkaline metal cell (9), (10) bimetal temperature sensors (11) exchange canal heater (13) ground electrode (14) optical bench.

come charged and to arc to their surroundings. Insulator failures were associated with the regions where the arcing had taken place. We believe that the charging of the insulators resulted from soft x-ray bombardment. It has been observed that the amount of extraneous light generated within the source box, after the source has been properly outgassed, has been greatly reduced by the addition of the shields, and no glow has been observed to come from within the insulator shields. The shields also provide protection against alkali-metal contamination of the insulators.

Alumina insulators were installed to replace the original stelitite insulators, which broke down under high voltage operation. As yet the results of this change are inconclusive.

d. The source of alkali metal vapor consists of a heated copper cell 2.9 cm in diameter by 2.5 cm long. The cell is surrounded by a nichrome heating unit which slides over the outside of the cell and attaches to the cell. The temperature of the cell is measured with a bimetal thermometer attached to the outside of the heating unit and read through a port in the side of the ion source box.
The alkali metal cell is placed below the exchange canal and attached to the canal with a stainless steel swage-lok fitting.

The system is designed so that a cell can be changed in less than 5 minutes after the source vacuum chamber has been let down to dry nitrogen.

e. Cooled electrodes have been placed at each end of the exchange canal on electrode supports which are independent of the heated exchange canal. They are electrically connected to the exchange canal and form elements in the focusing lenses preceding and following the exchange region. These electrodes are fitted with large cooled baffles which condense a large portion of the alkali metal flowing from the exchange region. After a period of normal operation of several days a litmus paper test of the interior walls of the source box showed a slight trace of alkali metal.

f. The focus electrode is cooled in order to reduce thermal stresses on the support insulators. In addition to preserving the focus electrode insulators, the cooled electrode traps vapors flowing toward the duoplasmatron.

g. The extraction electrode has undergone the most recent modification. It has been moved closer to the duoplasmatron aperture, and its shape modified to compensate for the change in position. The accelerating gap is set to 0.75 mm. This change has increased the He\textsuperscript{-} output by a factor of about 2.5 over that obtained in a configuration similar to the HVEC source where the spacing is 1.5 mm.

With the most recent modifications the source reached a peak output of 1 \( \mu \text{A} \) of He\textsuperscript{-} at an extraction voltage of about 14 kV. With the tandem at 7.667 MV, and with a 5 \( \mu \text{g/cm}^2 \) carbon stripper foil, 1 \( \mu \text{A} \) of beam was observed at the output of the accelerator. After momentum analysis and suitable focusing, a beam of 0.8 \( \mu \text{A} \) was placed on target in a scattering chamber.

With the extraction electrode-to-aperture spacing at 1.5 mm, and hydrogen exchange gas, the source, operating at only 30 kV, has produced 30 \( \mu \text{A} \) of H\textsuperscript{-} beam. The beams so far produced by the new source and those presently available from the original HVEC source indicate that some unknown difficulty external to the sources is, at the present time, reducing the total source output.
The new source has also performed satisfactorily for producing 0° beams.  
(T.D. Hayward, D.M. Patterson, and J.R. Tesmer)

1 Section 5.1 of this report.
2 Section 4.2 of this report.

12.8 Foil Stripper Assembly

The tandem (FN-3) was equipped with a foil stripper designed and built in this laboratory. This foil assembly is designed to be compatible with the existing gas stripper tube assembly and was intended to complement rather than replace this facility. The foil stripper design was initiated primarily to increase the fraction of ions produced with the higher ionic charges, and hence the intensity of high energy oxygen beams. As design progressed other advantages manifested themselves. A reduction in the gas load to be pumped by the high energy beam tube should reduce non-uniform electrical loading effects which influence beam trajectories. Also there is evidence that radiation damage to the tube section nearest the terminal will be greatly retarded.

The stripper assembly (Fig. 12.8-1) now consists of the remotely removable gas stripper tube, and the foil assembly which contains forty remotely positionable foil locations. The stripper foil assembly was located as close as possible to the high energy accelerating tube in order to minimize multiple scattering losses. To achieve a large number of foil positions, the foil wheel is constructed in a spiral configuration with a spiral brass rack soldered to the wheel, riding on a fixed pinion gear (Fig. 12.8-2). The foil positions are laid out after the soldering of the rack to assure accurate alignment. The foil wheel has flattened sides to allow insertion through a small cover plate, but the added room available in the box itself is utilized as the wheel is rotated. Thus the wheel may be removed and foils replaced without disturbing the drive mechanism and with minimum disturbance to vacuum seals. The foil wheel is positioned by driving the pinion gear through a bellows-sealed rotary feedthrough, thus eliminating moving seals to minimize the leak rate from the pressure vessel into the stripper box. This rotary feedthrough is in turn driven by a lucite rod from the low-energy base plate where a chevron-sealed feedthrough connects to the manually-operated positioner and foil indicator. This indicator has provision for eliminating the effects of backlash on the indicated position. The gas stripper tube is also removed and positioned by means of a lucite rod control.

The foils are held on small circular aluminum inserts 1/2 inch in diameter with a 5/16 inch hole. These are in turn held in the brass foil wheel by spring wire clips. The foils used to date have all been carbon and the thickness has
1. VERTICAL STEERING PLATES
2. FOIL STRIPPER ASSEMBLY
3. GAS STRIPPER MECHANISM
4. STRIPPER GAS INLET

Fig. 12.8-1. Tandem (FN-3) Stripper Assembly.
Fig. 12.8-2. Foil Stripper. (a) foil side (b) spiral rack

ranged from 5 to 20 gm/cm$^2$. The large number of foils was initially decided upon to allow for burning out a reasonable number before having to go into the machine to replace them. However, it has been found that, contrary to expectations, the foils seem to increase in thickness in the region bombarded by beam and when the resulting non-uniformities increase to the point where the beam energy spread becomes appreciable a new foil must be inserted. This buildup is also accompanied by the formation of wrinkles which accelerate the increase of non-uniformities. It would seem that the thinner the foil the better for most purposes.

The foil stripper has performed adequately and has caused few maintenance problems other than replacement of foils. The transmission, expressed as the percentage of H$^+$ ions at the low energy Faraday cup appearing as positive ions at the high energy cup, is 20-30% with the gas stripper and as high as 80-90% with the foil stripper. The ionic charge distributions for 7.5 MeV oxygen ions have been measured for the gas and foil strippers, and are illustrated in Fig. 12.8-3. The average ionic charge has increased by approximately one charge unit, while the beam intensity for the higher charge states has increased by a factor of approximately 10. (R.G. Clarke, J.S. Heagney, and R. Vandenbosch.

Fig. 12.8-3. Charge distributions for gas and foil stripping. A 10 µgm/cm$^2$ carbon foil was used for foil stripping.
13. APPENDIX

13.1 Nuclear Physics Laboratory Personnel

Faculty

John S. Blair, Professor
David Bodansky, Professor
John G. Cramer, Associate Professor
W. Kenneth Dawson, Visiting Professor
Arthur W. Fairhall, Professor
George W. Farwell, Professor
James D. Gerhart, Professor
I. Halpern, Professor
Fred H. Schmidt, Professor
Robert Vandenbosch, Professor
Stanley L. Whetstone, Visiting Professor

Nuclear Physics Laboratory Research Staff

Joseph P. Allen, Research Associate
Peter von Brentano, Senior Research Associate
Nelson W. Cue, Research Associate
Hiroyasu Ejiri, Senior Research Associate
Bernard Fernandez, Physicist
Anastasios Katsanos, Research Associate
Nolan F. Mangelson, Research Associate
Paul F. Mizera, Research Associate
Gary W. Phillips, Research Associate
Patrick Richard, Research Associate
William G. Weitkamp, Research Associate

Laboratory Supervisory Personnel

Harold Fauska, Senior Physicist; Research Electronics Supervisor;
Assistant Supervisor, Nuclear Physics Laboratory
Joseph S. Heagney, Senior Physicist
Peter Mocmjeovich, Engineer
John W. Orth, Acting Supervisor, Nuclear Physics Laboratory

Predoctoral Research Associates

Chemistry

Charles J. Bishop
Dennis G. Perry
Clifford Rudy
Robert W. Shaw, Jr.
Kevin L. Wolf
Physics

Wilfred J. Braithwaite
David Chamberlin
Gary M. Chenevert
Stephen N. Ferguson
Thomas D. Hayward
Robert H. Heffner
Roger A. Hinrichs
David L. Johnson
Wojciech A. Kolasinski
Ching C. Ling
Donald M. Patterson
David C. Shreve
Derek W. Storm
Joseph R. Tesmer
William R. Wharton

Research Assistants

Chemistry

Ronald Aley
Joseph Gonyeau

Physics

William J. Courtney
Juri Zemkau
William W. Jacobs
Robert H. Lewis
Dennis L. Oberg
William Q. Sumner
Howard H. Wieman

Full-Time Technical Staff

Machine Shop

Harvey E. Bennett, Foreman
Norman E. Gilbertson
Charles E. Hart, Assistant Foreman
Gustav E. Johnson
Edwin F. McArthur
Bernard Miller
Byron A. Scott
Anthony Virant
Allen L. Willman
Electronic and Electrical

Nancy J. Caling
Noel R. Cheney, Field Engineer
Laverne H. Dunning
Kyun-Ha Lee
Rod E. Stowell
Norman G. Ward

Technicians

Richard R. Clay
Emad Hussain
Carl E. Linder
Georgia J. Rohrbaugh
George E. Saling

Design & Drafting

Peggy Douglass
David W. Gough
Lewis E. Page

Accelerator Operators

Jacque M. Beechel
Cathea Stanley
Linda L. Stumpf

Others

Tylaine C. Hansen, Office Assistant
Sarah J. Harrington, Office Assistant
Shirley Kellenbarger, Chemist
Joanne M. Sauer, Chemist
Helene G. Turner, Administrative Secretary

Part-Time Technical Staff

Student Helpers

Gerald Eilenberg
Richard A. Gallaher
Elisabeth A. Jacobsohn
Timothy Kelleher
John G. Marckworth
Charles J. Peterson
James F. Peterson
Gary W. Roth
Dale E. Sayers
Patrick B. Stanton

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On leave from University of Alberta, Edmonton, Canada.
On leave from Los Alamos National Laboratory.
Now at NASA, Oklahoma.
Now at Max Planck Institute, Heidelberg, Germany.
Now at State University of New York, Stony Brook, N.Y.
Now at Saclay, France.
Now at Aerospace Corporation, Los Angeles, California.
Now at University of Pittsburgh, Pittsburgh, Pennsylvania.
Terminated.
Research Assistant without stipend.
On leave from the University.
Retired.
Now at Atomic Energy Centre, Pakistan

13.2 Advanced Degrees Granted, Academic Year 1967-1968

N. W. Cue: Ph.D. "An Experimental Study of Low Energy Protons Following Deuteron Induced Reactions: Spectral Fluctuations and Decay from Isobaric Analogue States".

W. A. Kolasinski: Ph.D. "Studies of Proton Spin Flip in Inelastic Scattering from Carbon and Nickel Isotopes".

13.3 List of Publications


"Charge Exchange Effects in the (d,p) Reaction Leading to States in $^{93,95}$Zr, $^{93,95}$Mo and $^{141}$Ce", R. Heffner, C. Ling, N. Cue and P. Richard, Phys. Letters 26B, 150 (1968).


Publications in Press or Submitted for Publication:


"Electric Dipole Transition from the $2f_{7/2}$ Isobaric Analogue Resonance to the $2d_{5/2}$ Ground State in $^{141}$Pr", H. Ejiri, P. Richard, S. Ferguson, R. Heffner and D. Perry (submitted to Phys. Rev. Letters).

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"Proton Decay of Analogue States Formed in the (d,n) Reaction", N. Cue and P. Richard (submitted to Phys. Rev.).


"Inelastic Scattering of 42-MeV Alpha Particles from $\kappa^{39}$ and $\nu^{51}$, R.J. Peterson (submitted for publication).


"(a, Li) Reactions on B$^{11}$, N$^{15}$ and P$^{19}$, P.F. Mizera and J.B. Gerhart (to be published in Phys. Rev.).


Papers Given at Meetings and Conferences:


"Anomalies in the (d,p) Cross Sections Leading to States in $^{93,95}$Zr, $^{93,95}$Mo, and $^{141}$Ce", P. Richard, R. Heffner, C. Ling and N. Cue, Bull. Am. Phys. Soc. 12, 1196 (1967).


