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ANNUAL REPORT 1975

JOHN H. WILLIAMS LABORATORY
OF
NUCLEAR PHYSICS
UNIVERSITY OF MINNESOTA
September, 1975

U. S. Energy Research and Development Administration

Contract E(11-1)-1265

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INTRODUCTION

This report summarizes the work by the staff of the John H. Williams Laboratory of Nuclear Physics at the University of Minnesota during the year ending August 1975. The work was supported by the United States Energy Research and Development Administration under contract E(11-1)-1265.

Part A of this report describes the research program of the laboratory. The experimental work conducted with the model MP Tandem Van de Graaff machine made use of beams of hydrogen, helium, carbon, and oxygen isotopes. Target elements ranged throughout the periodic table. The experiments using laser techniques to study nuclear properties via measurements of atomic hyperfine structure were continued. Some of the experimental and theoretical work reported here was done in collaboration with persons at other laboratories.

Part B of this report describes some developments of experimental equipment and techniques. Part C reports on the operation of the Tandem during the past year and describes a few changes that have been made in the machine to improve the reliability of its operation. Part D describes work carried on at Los Alamos Scientific Laboratory by members of the Williams Laboratory Staff who are working on the preparation of equipment and experiments at the Meson Physics Facility.

An Appendix lists laboratory personnel, publications of staff and students, and degrees granted to graduate students.
A. RESEARCH PROGRAM

I. SCATTERING AND REACTIONS OF LIGHT NUCLEI

1. Measurement of p+p Angular Distributions from 6 to 14 MeV(lab)

P. M. Hegland, J. A. Koepke, J. S. Lilley, and R. E. Brown

Our previous attempts\textsuperscript{1} to measure the relative differential cross section for p+p scattering at 19.7 MeV(lab) have been thwarted by the inoperability of the accelerator at that energy. However, recent work\textsuperscript{2-5} on the p+p interaction at lower energies has shown inconsistencies in the deduced, central, p-wave parameter $\Delta_c$. This is illustrated in Fig. 1-1. We have set out therefore to measure p+p angular distributions at several of these lower energies. At present we have completed measurements at lab energies 5.957, 6.968, 8.030, and 9.918 MeV, and data taking at 13.60 MeV will be begun soon. These energies were chosen because they correspond to those of previous\textsuperscript{4,5} measurements of p+p scattering which used gas targets and which have uncertainties of less than 1% in the scale of absolute cross section. At these energies the differential cross sections determine principally two parameters, $\delta_{00}$ and $\Delta_c = (\delta_{10} + 3\delta_{11} + 5\delta_{12})/9$, where the $\delta_{ij}$ are the phase shifts. The s-wave phase shift $\delta_{00}$ is sensitive mainly to the absolute normalization of the differential cross section, and the p-wave parameter $\Delta_c$ is sensitive mainly to its shape. Therefore, our experiment, which consists in measuring relative differential cross sections using solid polystyrene (CH) targets\textsuperscript{1} and monitor detectors, is designed to yield information on $\Delta_c$, but not on $\delta_{00}$.

The data-detector system consisted of a stack of two, cooled, surface-barrier detectors surrounded by a grounded aluminum shield. This stack was placed behind a collimator 3-mm wide by 6-mm high which
was 113.7 cm from the target position in the eight-foot windowless scattering chamber. The use of this chamber allows the data-detector angle to be set to an accuracy of ±0.01° and allows data to be obtained both left and right of the incident beam out to a maximum lab angle of 16°. The sum of the signals from the two detectors was pulse-height analyzed, and a coincidence requirement was imposed on the two signals in order to reduce background. Proton energy resolutions as good as 22 keV FWHM have been obtained with this system.

The monitor-detector system consisted of two Li-drifted Si detectors placed at equal angles on each side of the incident beam. Each detector subtended a solid angle about ten times that subtended by the data detector. Three single-channel analyzers (SCA) were set to analyze three regions of each monitor pulse-height spectrum. One SCA was set to analyze protons elastically scattered from carbon, one was set to analyze protons elastically scattered from hydrogen, and one was set to monitor background near this latter p+H scattering peak. Ratios of proton counts recorded by one monitor detector to those recorded by the other give information on changes in both beam position and beam angle during data accumulation, and the sum of the background-corrected proton counts from p+H scattering recorded by the two monitor detectors is used to normalize the p+H scattering measured by the data detector.

A careful study was made of the possible effects of multiple Coulomb scattering in the polystyrene targets by measuring proton scattering yields for target thicknesses between 40 and 800 μg/cm². These measurements were made at a variety of beam energies and data-detector angles. No effect of multiple scattering was observed within the statistical accuracy of 0.35%.
A critical test of many aspects of the measurement system was made by measuring the shape of the pure Rutherford $^1\text{H}^7\text{Au}$ elastic differential cross section at 8.030 MeV(lab). The rate of change of this cross section with angle is several orders of magnitude greater than than of the p+p differential cross section. The excellent reproduction of the Rutherford shape which we obtained is shown in Fig. 1-2.

The p+p data were taken mostly with targets of 400 to 600 µg/cm$^2$ thickness. At each scattering angle a total of 80,000 proton counts from p+H scattering was recorded by the data detector. Half of these counts were obtained with the target angle set at 0° and half with it set at 180°, both positions being such that the target plane is perpendicular to the incident beam. In addition, at lab angles ≤16°, half of the 80,000 counts were obtained with the data detector set to the left of the incident beam and half with it set to the right. These procedures allow data to be obtained which are relatively insensitive to slight beam or target misalignments. The counting rate was kept low enough that electronic dead times were usually less than 1.5%. Dead time corrections and the angle-dependent corrections for counting losses due to nuclear reactions in the data detector were made on-line. Our preliminary angular distributions are shown in Fig. 1-3.

At angles less than about 12° the protons from p+C scattering are close enough in energy to those from p+H scattering that care must be taken in extracting the number of p+H scattering events from the data detector pulse-height spectrum. A computer code is being developed.
to perform this extraction. Proper analysis of the forward-angle data may result in corrections of several percent to the results of the present preliminary analysis.

After all the data are obtained and reduced, a phase shift analysis will be performed to extract $\Delta C$ as a function of energy. Present tentative indications are that our results will be in better agreement with those of Ref. 5 than of Ref. 2-4.

References


8. We thank Dr. R. K. Snyder for writing the original code and for help during the initial phases of the experiment.
Fig. 1-1. $\Delta_c$ parameter from individual-data-set analyses of J. Holdeman, P. Signell, and M. Sher, Phys. Rev. Lett. 24, 243 (1970) and of Ref. 5. The result of the analysis of the data of Ref. 2 is represented by $\Delta$, of Ref. 3 by $X$, of Ref. 4 by $\triangle$, of Ref 5 by $0$. 

\[ \Delta_c \text{ (deg)} \]

\[ E_{\text{lab}} \text{ (MeV)} \]
Fig. 1-2. $^{197}\text{Au}(p,p)^{197}\text{Au}$ angular distribution at a lab energy of 8.030 MeV, plotted as a ratio to the Rutherford cross-section in arbitrary units. The errors shown are statistical only.
Fig. 1-3. $^1\text{H}(p,p)^1\text{H}$ relative angular distributions.
Resonating-Group Calculations with Coulomb Exchange

for d+d Scattering

P. M. Hegland and R. E. Brown

The Coulomb-exchange kernel has been added\textsuperscript{1} to the resonating-group code for the d+d system, and various checks have been made to insure it's correctness.

Three things have become apparent while comparing the calculations to our experimental data\textsuperscript{2}. The addition of the Coulomb exchange terms makes very little difference in the phase shifts, 1° or less, and therefore in the elastic differential cross-section. The best fits (minimum $\chi^2$ per datum) to the elastic differential cross-section data are found for $u$-values of 1.3 or larger and the strengths $W_0$, $W_1$, and $W_2$ of the imaginary potentials in the three spin states near values interpolated from Ref. 3. The best fits to the differential cross-sections give a total reaction cross-section between 600 and 700 mb compared to our measured value of 385 ± 20 mb at 17.50 MeV (lab). When the $W_0$, $W_1$, and $W_2$ are adjusted to yield a reaction cross-section near the measured value, the $\chi^2$ per datum goes from 2-10 to 150-250.

Fig. 2-1 shows the measured elastic differential cross-section at 17.50 MeV along with calculations using several $u$ and $W_s$ parameters.

References

Fig. 2-1. Measured d + d → d + d cross-sections, with a total error of 1.5%, for $E_L = 17.50$ MeV are represented by . The solid line represents a calculation with $u = 1.4$, $W_1 = 0.11$ MeV, $W_2 = 1.70$ MeV, $W_3 = 0.58$ MeV, and with Coulomb exchange. The $\chi^2$ per datum = 2.43 for the elastic scattering and a calculated total reaction cross-section of 683 mb. The dashed line represents a calculation that gives the measured total reaction cross-section, but the $\chi^2$ per datum for the elastic scattering is equal to 215.


3. Study of \( p + ^3 He \) Elastic Scattering from 19 to 48 MeV

R. E. Brown, A. M. Sourkes*, and W. T. H. van Oers*

The \( p + ^3 He \) elastic scattering measurements\(^1, 2\) using the University of Manitoba cyclotron are almost finished. Complete or nearly complete differential cross sections (\( \Theta_{\mathrm{lab}} = 10^\circ \) to \( 170^\circ \)) have been measured at the approximate lab energies of 19.48, 21.29, 25.00, 27.50, 30.00, 35.00, 40.00, 45.00, and 47.50 MeV. Computer-aided data reduction is currently in progress.

References

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4. **Total Reaction Cross Sections for \( p + ^3_\text{He} \) from 18 to 48 MeV**


One of the basic measurements of importance for the understanding of the interaction between two nuclei is that of the total reaction cross section \( \sigma_R \). For example, absorption processes affect the elastic scattering probability by removing flux from that otherwise available for scattering, and therefore, measured values for \( \sigma_R \) are necessary to allow the proper restrictions to be placed on the amount of absorption included in theoretical or phenomenological analyses of elastic-scattering data. Phase-shift extraction and optical-model fitting are types of such analyses. The inclusion of phenomenological imaginary potentials in resonating-group calculations\(^1\) for light systems has also made it important to have \( \sigma_R \) measurements for such systems. In the present work we report measurements of \( \sigma_R \) for the systems \( p + ^3\text{He} \) and \( p + ^4\text{He} \) over the proton energy range 18 to 48 MeV(lab). An anticoincidence, beam-attenuation technique\(^2\) is used in these measurements; a brief report of the experimental results has been given\(^3\).

The University of Manitoba 50-MeV Cyclotron was used to provide proton beams of the desired energies. The beam was momentum analyzed by a bending magnet and was tightly collimated before impinging on the total-reaction-cross-section apparatus. A schematic diagram of this apparatus is shown in Fig. 4-1. Detectors 1 to 5 are NE-102 plastic scintillators, and detector 6 is a CsI(Na) scintillator. A trigger signal is generated whenever detector 1 produces a signal.
which is in coincidence with one produced by detector 2, and at the same time, no signal is produced by either of the annular detectors 3 or 4. The presence of such an event signifies that a proton was incident on the gas-cell entrance foil. Particles emerging from the gas cell in the forward cone enter the detector assembly composed of the thin, small-diameter, plastic disk 5 and the stopping detector 6. The discriminator settings are such that detector 5 is sensitive to essentially all the charged particles which enter it, and detector 6 is sensitive only to the elastically scattered protons which enter it. A signal which is generated by the occurrence of signals from detector 5, or 6, or both, is recorded as a "nonattenuation" event. The number \( I \) of such nonattenuation events, when combined with appropriate corrections, helps to determine how many of the number \( I_0 \) of incident protons underwent reactions in the gas cell. This manner of operation of detector 5 allows a great reduction in the correction which need be applied for reactions which occur in stopping detector 6. A detailed description of the reaction apparatus and electronic circuitry is given in Ref. 2.

The experiment was carried out by making two separate attenuation measurements at every beam energy, one with the gas cell filled with helium and the other with the gas cell evacuated. The measurements made with the evacuated cell are necessary to correct the measurements made with the filled cell for the reactions and large-angle scatterings which occur in the cell foils. Therefore, the measurements at each energy yield directly an uncorrected reaction cross section \( \sigma_{\text{un}} \) given by
\[ \sigma_{\text{un}} = \frac{1}{n_t} \left\{ \frac{I_0 - I}{I_0} - \frac{i_0 - i}{i_0} \right\} , \tag{1} \]

where \( I_0 \) and \( I \) are the numbers of incident protons and nonattenuation events, respectively, for the filled-cell measurements, \( i_0 \) and \( i \) are the corresponding quantities for the evacuated-cell measurements, \( n \) is the number of helium nuclei per unit volume, and \( t \) is the length of the gas cell. To obtain the total reaction cross section \( \sigma_R \), the quantity \( \sigma_{\text{un}} \) must be corrected for the following processes: (i) elastic-scattering events counted as attenuation events, (ii) reaction products detected as nonattenuation events, (iii) elastically recoiling helium nuclei detected as nonattenuation events, (iv) nuclear reactions occurring in stopping detector 6, and (v) other small corrections, some of which result from the fact that the energy of protons emerging from the gas cell is several hundred keV higher when the cell is evacuated than when it is filled.

The uncorrected cross sections \( \sigma_{\text{un}} \), the corrections to \( \sigma_{\text{un}} \), and the final corrected cross sections \( \sigma_R \) are given in Tables 4-1 and 4-2. A detailed discussion of the corrections is given elsewhere.

In Fig. 4-2 our measured values of \( \sigma_R \) for the \( p + ^3\text{He} \) interaction are compared with the results of two other experiments. The crosses show the \( \sigma_R \) values of Ref. 5 for the \( n + ^3\text{H} \) system, which is the charge-conjugate system to \( p + ^3\text{He} \). These values are in reasonable agreement with our measurements; however, the large uncertainties in the \( n + ^3\text{H} \) results preclude a very meaningful comparison. The triangles show estimates based on the measurements of the reactions \( p + ^3\text{He} \rightarrow d + 2p \) and \( p + ^3\text{He} \rightarrow n + ^3p \) reported in Ref. 6. Again there is agreement, but again the errors are large.
An optical-model analysis with exchange terms of \( p + ^3\text{He} \) elastic scattering over an energy range encompassing that of the present experiment has recently been carried out\(^7\). The total reaction cross sections (not shown) yielded by the imaginary potentials of this analysis are not smooth functions of energy and generally are in marked disagreement with the present measurements. An 85-MeV analysis\(^8\) with an exchange term in the real, central part of the optical potential gave \( \sigma_R = 140 \text{ mb} \), a value which would seem to agree with a reasonable extrapolation of the present results.

The two lowest-energy measurements of the \( p + ^4\text{He} \) total reaction cross section listed in Table 4-2 were made below the first reaction threshold at 23.02 MeV (the first reaction possible is \( p + ^4\text{He} \rightarrow d + ^3\text{He} \)). The fact that these two measurements are consistent with zero serves as a useful check of the experimental method. In Fig. 4-3 the 14 remaining \( \sigma_R \) measurements are compared with other experimental results. The triangle shows the result of Ref. 9 at \( E_p = 53 \text{ MeV} \), which was obtained by analyzing \( p + ^4\text{He} \) reaction events in a helium-filled cloud chamber. The crosses indicate values deduced by applying detailed balance to measurements\(^10\) on the reaction \( d + ^3\text{He} \rightarrow p + \alpha \). Above 24.86 MeV additional reaction channels become open, and therefore, the crosses in Fig. 4-3 show increasing deviation from the present data points as the energy increases.

We also compare our measured \( \sigma_R \) values with those (not shown) which result from a recent phase-shift analysis\(^11\) of \( p + ^4\text{He} \) elastic-
scattering data. The results for \( \sigma_R \) given by the phase shifts are in excellent agreement with the present measurements. An extension\(^{12}\) of the analysis to higher energies employed the present measurements of \( \sigma_R \) as constraints in the fitting.

In Ref. 13 an optical-model analysis was performed on \( p + ^4\text{He} \) elastic-scattering data in the energy range 30 to 55 MeV. The best-fit parameters yielded total reaction cross sections of about 150 mb, which are much too large. When \( \sigma_R \) was restricted to values around 95 mb, which is more reasonable in view of our measurements, the fits to the elastic data were significantly worsened. The optical-potential analysis of Ref. 8, which was mentioned previously as having been applied to \( p + ^3\text{He} \) scattering at 85 MeV, was also applied to \( p + ^4\text{He} \) scattering at the same energy. In contrast to the apparent consistency between our measurements and the \( \sigma_R \) value obtained from the \( p + ^3\text{He} \) analysis, the value of about 190 mb obtained from the \( p + ^4\text{He} \) analysis seems to be too large to be reproduced by a reasonable extrapolation of the present data.

Comparisons between results of resonating-group calculations and elastic scattering data taken at energies where reaction channels are open have been facilitated by the incorporation of phenomenological imaginary potentials into the calculations. The existence of experimental values of the total reaction cross section \( \sigma_R \) allows important restrictions to be placed on the imaginary potential. On comparing our measured \( \sigma_R \) values with those resulting from a previous resonating-group calculation\(^{14}\), we find that the calculated
values are generally 30 to 40% smaller than the experimental values. We have therefore redone the analysis of Ref. 14 to learn whether or not reasonable fits to the elastic-scattering data can be obtained when the imaginary potential is required to produce $\sigma_R$ values consistent with the present measurements. The formulation of the calculation follows that of Ref. 14 in which an imaginary potential $iW$ is introduced into the integrodifferential equation derived for $p + ^4\text{He}$ scattering with the resonating-group method. The quantity $W$ is given the form

$$W = (1 + C_I p^r)U(r), \quad (2)$$

where

$$U(r) = -U_0 \left\{ \frac{1}{1 + e^{(r-R)/a}} + \frac{4e^{(r-R)/a}}{[1 + e^{(r-R)/a}]^2} \right\}. \quad (3)$$

In Eq. (2) $p^r$ is a space-exchange operator, and the parameter $C_I$ determines the strength of the exchange part of $W$ relative to the nonexchange part. Equation (3) is not of the pure surface form used in Ref. 14, but instead has the form used in studies of other systems. The analysis is performed by solving Eq. (1) of Ref. 14 at six energies in the c.m. energy range 23 to 44 MeV. The radius $R$ and diffuseness $a$ of Eq. (3) are set at $R = 2.25$ fm and $a = 0.5$ fm, and visual fitting to the data, including the present $\sigma_R$ values, is carried out by varying the two parameters $U_0$ and $C_I$. In Table 4-3 are listed the resultant values of $U_0$ and $C_I$ along with the calculated total reaction cross sections $\sigma_R$, which were restricted in the fitting to agree with the present measurements. The $C_I$ values of Table 4-3 are the same as those of Ref. 14; therefore, they do not
seem to be very sensitive to the actual form used for the imaginary potential. No uncertainties in $C_I$ are indicated in Table 4 -3; however, they are very similar to those shown in Fig. 7 of Ref. 14 ($\pm 0.1$, at best).

In Fig. 4-4 some of the results of the calculation are compared with experimental data. In general the fits are similar to those of Ref. 14, although they are sometimes slightly worse. The most striking feature of Fig. 4-4 is the indication of a worsening of the fit to the polarization as the energy increases. This was also observed in Ref. 14, and is probably caused by the use of a nucleon-nucleon spin-orbit interaction rather than a tensor interaction in the resonating-group calculation. The range and depth of this spin-orbit potential were chosen to reproduce noncentral features (splitting of the p-wave phase shifts) in the $p + ^4$He system at low energies. Such noncentral features are actually caused principally by the tensor interaction, and therefore, it is not surprising that a spin-orbit potential selected to reproduce such features over a restricted energy range may not be correct over a broad energy range. The most significant difference between the real parts of the phase shifts obtained from the resonating group calculation and those obtained from the phase-shift analysis of Ref. 11 is that the calculated splitting of the d-wave phases is about twice as large as found from the phase-shift analysis. Of course, the method just mentioned of including noncentral forces in the calculation is relevant to the understanding of this difference. The most striking
difference between the imaginary parts of the phase shifts obtained from the present calculation and those obtained from the phase-shift analysis is that the calculated imaginary parts are largest for $\ell = 1$, whereas the phase-shift analysis yields the largest imaginary parts for $\ell = 2$.

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References concluded on p. 23
TABLE 4-1. $p + ^3\text{He}$ cross sections in mb at proton lab energies $E_p$ in MeV. Listed are values for the uncorrected cross sections $\sigma_{un}$ of Eq. (I), for the corrections to $\sigma_{un}$ with their associated signs given in parentheses, and for the resulting total reaction cross sections $\sigma_R$ with their standard deviations. The standard deviation in $\sigma_{un}$ and in the elastic corrections is 2%.

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<td>380</td>
<td>308</td>
<td>3.0</td>
<td>...</td>
<td>1.0</td>
<td>...</td>
<td>1.0</td>
<td>73 ± 10</td>
</tr>
<tr>
<td>25.05</td>
<td>416</td>
<td>321</td>
<td>4.0</td>
<td>0.4</td>
<td>1.0</td>
<td>3.0</td>
<td>1.0</td>
<td>94 ± 11</td>
</tr>
<tr>
<td>27.55</td>
<td>314</td>
<td>212</td>
<td>5.0</td>
<td>0.4</td>
<td>4.0</td>
<td>...</td>
<td>0.9</td>
<td>103 ± 8</td>
</tr>
<tr>
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<td>295</td>
<td>191</td>
<td>6.0</td>
<td>0.3</td>
<td>4.0</td>
<td>...</td>
<td>0.8</td>
<td>106 ± 8</td>
</tr>
<tr>
<td>35.00</td>
<td>245</td>
<td>142</td>
<td>6.5</td>
<td>0.2</td>
<td>2.5</td>
<td>...</td>
<td>0.8</td>
<td>106 ± 6</td>
</tr>
<tr>
<td>40.00</td>
<td>214</td>
<td>103</td>
<td>7.0</td>
<td>0.2</td>
<td>2.5</td>
<td>...</td>
<td>0.7</td>
<td>115 ± 5</td>
</tr>
<tr>
<td>45.00</td>
<td>190</td>
<td>75</td>
<td>8.0</td>
<td>0.2</td>
<td>3.0</td>
<td>...</td>
<td>0.6</td>
<td>120 ± 5</td>
</tr>
<tr>
<td>47.65</td>
<td>185</td>
<td>66</td>
<td>8.0</td>
<td>0.1</td>
<td>3.0</td>
<td>...</td>
<td>0.5</td>
<td>124 ± 5</td>
</tr>
</tbody>
</table>
TABLE 4-2. \( p + ^4\text{He} \) cross sections in mb at proton lab energies \( E_p \) in MeV. Listed are values for the uncorrected cross sections \( \sigma_{un} \) of Eq. (1), for the corrections to \( \sigma_{un} \) with their associated signs given in parentheses, and for the resulting total reaction cross sections \( \sigma_R \) with their standard deviations. The standard deviation in \( \sigma_{un} \) and in the elastic corrections is 2\%.

<p>| ( E_p ) | ( \sigma_{un} ) | elastic recoils reactions light exit ( \sigma_R ) |
|---|---|---|---|---|---|
| ( 18.20 ) | ( 549 ) | ( 556 ) | ( \ldots ) | ( 0.8 ) | ( 0.9 ) | ( -9 \pm 16 ) |
| ( 19.90 ) | ( 514 ) | ( 514 ) | ( \ldots ) | ( 1.0 ) | ( 0.9 ) | ( -2 \pm 15 ) |
| ( 23.35 ) | ( 452 ) | ( 400 ) | ( 0.9 ) | ( 0.8 ) | ( 0.9 ) | ( 51 \pm 12 ) |
| ( 24.00 ) | ( 444 ) | ( 389 ) | ( 1.0 ) | ( 0.6 ) | ( 2.0 ) | ( 0.9 ) | ( 52 \pm 12 ) |
| ( 24.45 ) | ( 423 ) | ( 363 ) | ( 1.1 ) | ( 0.6 ) | ( 0.8 ) | ( 0.9 ) | ( 59 \pm 11 ) |
| ( 25.70 ) | ( 399 ) | ( 341 ) | ( 1.3 ) | ( 0.8 ) | ( 0.7 ) | ( 0.8 ) | ( 57 \pm 11 ) |
| ( 27.00 ) | ( 376 ) | ( 319 ) | ( 1.4 ) | ( 1.4 ) | ( 1.2 ) | ( 0.8 ) | ( 55 \pm 10 ) |
| ( 28.00 ) | ( 368 ) | ( 303 ) | ( 1.5 ) | ( 1.3 ) | ( 0.7 ) | ( 0.8 ) | ( 64 \pm 10 ) |
| ( 30.20 ) | ( 345 ) | ( 272 ) | ( 1.7 ) | ( 2.7 ) | ( 0.9 ) | ( 0.7 ) | ( 70 \pm 9 ) |
| ( 32.25 ) | ( 315 ) | ( 241 ) | ( 2.1 ) | ( 1.8 ) | ( 0.6 ) | ( 0.7 ) | ( 73 \pm 8 ) |
| ( 34.10 ) | ( 294 ) | ( 213 ) | ( 2.4 ) | ( 2.5 ) | ( 2.2 ) | ( 0.6 ) | ( 0.7 ) | ( 82 \pm 7 ) |</p>
<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$\sigma_{un}$</th>
<th>elastic</th>
<th>reaction products</th>
<th>recoils</th>
<th>reactions in 6</th>
<th>light guide</th>
<th>exit foil</th>
<th>$\sigma_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.00</td>
<td>272</td>
<td>179</td>
<td>3.3</td>
<td>2.4</td>
<td>2.1</td>
<td>0.8</td>
<td>0.6</td>
<td>95 ± 7</td>
</tr>
<tr>
<td>39.60</td>
<td>253</td>
<td>154</td>
<td>6.3</td>
<td>2.4</td>
<td>1.5</td>
<td>0.6</td>
<td>0.6</td>
<td>105 ± 6</td>
</tr>
<tr>
<td>42.30</td>
<td>233</td>
<td>132</td>
<td>6.9</td>
<td>2.3</td>
<td>2.0</td>
<td>0.4</td>
<td>0.5</td>
<td>107 ± 6</td>
</tr>
<tr>
<td>44.70</td>
<td>218</td>
<td>115</td>
<td>7.6</td>
<td>2.1</td>
<td>2.8</td>
<td>0.6</td>
<td>0.5</td>
<td>109 ± 6</td>
</tr>
<tr>
<td>47.90</td>
<td>207</td>
<td>98</td>
<td>8.3</td>
<td>1.8</td>
<td>3.8</td>
<td>0.6</td>
<td>0.5</td>
<td>114 ± 5</td>
</tr>
</tbody>
</table>

16. M. K. Brussel and J. H. Williams, Phys. Rev. 106, 286 (1957);

TABLE 4-3. Parameters $U_o$ and $C_I$ of the imaginary potential and calculated total reaction cross sections $\sigma_R$ from a resonating-group analysis of the $p + ^4$He system at c.m. energies $E$. The imaginary potential is given by Eqs. (2) and (3) with $R = 2.25$ fm and $a = 0.5$ fm.

<table>
<thead>
<tr>
<th>$E$ (MeV)</th>
<th>$U_o$ (MeV)</th>
<th>$C_I$</th>
<th>$\sigma_R$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.04</td>
<td>0.75</td>
<td>+0.20</td>
<td>60.7</td>
</tr>
<tr>
<td>24.8</td>
<td>0.95</td>
<td>-0.25</td>
<td>70.3</td>
</tr>
<tr>
<td>32.0</td>
<td>1.75</td>
<td>-0.70</td>
<td>102.8</td>
</tr>
<tr>
<td>36.8</td>
<td>2.0</td>
<td>-0.70</td>
<td>110.8</td>
</tr>
<tr>
<td>38.2</td>
<td>2.1</td>
<td>-0.70</td>
<td>114.1</td>
</tr>
<tr>
<td>44.0</td>
<td>2.2</td>
<td>-0.55</td>
<td>117.5</td>
</tr>
</tbody>
</table>
Fig. 4-1. Schematic diagram of the total-reaction-cross-section apparatus. Detectors 1, 2, 3, and 4 determine whether or not a proton was incident on the entrance foil of the gas-target cell, and detectors 5 and 6 help determine whether or not that proton underwent a reaction in the cell.
Fig. 4 - 2 Total reaction cross sections $\sigma_R$ for the $p + ^3\text{He}$ interaction at proton lab energies $E_p$. The arrow indicates the position of the first reaction threshold. The circles represent the present measurements listed in Table 4 - 1, the crosses show the measurements of Ref. 5 for the $n + ^3\text{He}$ system, and the triangles indicate values obtained from Ref. 6.
Fig. 4-3. Total reaction cross sections $\sigma_R$ for the $p + ^4\text{He}$ interaction at proton lab energies $E_p$. The arrow indicates the position of the first reaction threshold. The circles represent the present measurements listed in Table 4-2, the triangle shows results from Ref. 9, and the crosses represent values deduced by applying detailed balance to measurements (Ref. 10) on the reaction $d + ^3\text{He} \rightarrow d + \alpha$. 
Fig. 4-4. Comparison of the $p + ^4\text{He}$ resonating-group calculations (curves) with the experimental data (points) of Ref. 15. The parameters of the imaginary potential are given in Table 4-3.
5. Measurement of $^3\text{He} + ^3\text{He}$ Reaction Cross Sections


During the past year measurements have begun for $^3\text{He} + ^3\text{He}$ reactions similar to those made for $d + d$ (Ref. 1) and $^3\text{He} + ^4\text{He}$ (Ref. 2). The possible $^3\text{He} + ^3\text{He}$ reactions which can occur, their Q-values, and their threshold energies are given in Table 5 -1. All reactions produce three or more particles in the final state, thereby yielding continuous energy distributions for each reaction product. The total reaction cross section $\sigma_R$ is the sum of all partial reaction cross sections, integrated over the continuum energy distributions and over a $4\pi$ solid angle.

Let $\sigma_x$ stand for the total cross section for the production of particle $x$. It is possible to write down each of the production cross sections in terms of the reaction cross sections. The results are

$$\sigma_n = \sigma(2pn^3\text{He}) + \sigma(3pnd) + 2\sigma(4p2n),$$
$$\sigma_p = 2\sigma(2p\alpha) + \sigma(pd^3\text{He}) + 3\sigma(3pt) + 2\sigma(2p^3\text{He}) + 2\sigma(2p2d) + 3\sigma(3pnd) + 4\sigma(4p2n),$$
$$\sigma_d = \sigma(pd^3\text{He}) + 2\sigma(2p2d) + \sigma(3pnd),$$
$$\sigma_t = \sigma(3pt),$$
$$\sigma_{^3\text{He}} = \sigma(pd^3\text{He}) + \sigma(2pn^3\text{He}),$$
$$\sigma_{^3\text{He}} = \sigma(2p\alpha).$$

The total reaction cross section $\sigma_R$ can be expressed in terms of the production cross sections as

$$\sigma_R = \frac{1}{4}(\sigma_p + \sigma_d + \sigma_t) + \frac{1}{2}(\sigma_{^3\text{He}} + \sigma_{^3\text{He}}).$$

It is evident from this expression that $\sigma_R$ may be measured by detecting charged particles only.
Below the 2p2d threshold (21.94 MeV) a simplification occurs, and the expression for the total reaction cross section becomes

\[ \sigma_R = \sigma_\alpha + \sigma_t + \sigma_3^{\text{He}}. \]  

(3)

If deuterons are detected as well, the individual reaction cross sections can also be determined by the equations

\[ \sigma(2p\alpha) = \sigma_\alpha \]
\[ \sigma(pd^{\text{He}}) = \sigma_d \]
\[ \sigma(3pt) = \sigma_t \]
\[ \sigma(2pn^{\text{He}}) = \sigma_3^{\text{He}} - \sigma_d \]  

(4)

Below the 2p2d threshold it is not necessary to detect protons in order to measure the total or the individual reaction cross sections. Between 21.94 MeV and 26.39 MeV (the 3pnd threshold) the individual cross sections may be measured, provided protons are detected; however, the expressions are more complicated than Eq. (4). Above 26.39 MeV the individual cross sections cannot be determined unless neutrons are detected, and above 30.84 MeV it is not possible to determine the individual cross sections unless coincidence techniques are used. Nevertheless, at any energy above 21.94 MeV the total reaction cross section may be determined from Eq. (2).

Because of the simplifications that exist at energies below the 2p2d threshold, it was decided to begin the experiment at 21.7 MeV and to detect deuterons, tritons, \(^3\text{He}\) particles and \(\alpha\) particles. A three-detector telescope was assembled consisting of Si surface-barrier detectors of 24 \(\mu\text{m}\), 48 \(\mu\text{m}\) and 700 \(\mu\text{m}\) thicknesses. For detecting \(^3\text{He}\) and \(\alpha\) particles the 24-\(\mu\text{m}\) detector was used as a \(\Delta E\) detector and the 48- and 700-\(\mu\text{m}\) detectors were used together as the stopping detector in a standard
particle identification system. Deuterons and tritons were detected by using the 24- and 48-μm detectors together as a 72-μm ΔE detector and the 700-μm detector was then the stopping detector. Typical particle pulse-height spectra are shown in Fig. 5-1.

The target gas, 99.9% pure 3He at about 400 Torr, was contained in a 23.9-mm diam cylindrical gas cell with a 6.3-μm Kapton foil window and was located at the center of an ORTEC scattering chamber. Experimental details are similar to those previously reported.1,2

In order to integrate the continuum particle spectra over energy and angle, the method developed in Ref. 1 for the d + d reaction was used. This method makes use of the fact that the identity of the target nucleus and projectile causes all cross sections to be symmetric about 90° in the c.m. system. Thus, the total cross section for a particular reaction may be measured by integrating the c.m. energy spectra from the maximum possible energy to zero energy and from 0° to 90°. The result is then multiplied by 2. In the laboratory system, this corresponds to integrating a continuum energy spectrum at a given lab angle from the the maximum energy down to an energy E*, where E* is the energy for which the detected particle is emitted at 90° in the c.m. system. These energy-integrated spectra are then integrated over lab angle to yield the total particle production cross section. As shown in Ref. 1, the fact that at a given laboratory angle the value of E* depends only on the particle type being detected and is independent of the particular reaction producing that particle means that all particles of a given type may be detected and integrated together without the need of coincidence measurements.
Spectra of tritons, deuterons, $^3$He and $\alpha$ particles are shown in Fig. 5-1 for a $^3$He bombarding energy of 21.7 MeV and a laboratory detector angle of 15°. For each spectrum the maximum energy for the possible reactions is shown by arrows near the high-energy end and the energies $E^*$ also are shown by arrows at lower energies. Energy calibration of the spectra was obtained by putting deuterium gas in the target cell and measuring as a function of angle the pulse height of scattered $^3$He, recoil deuterons, and $\alpha$ particles from the reaction $^3$He + $^2$H → $^4$He + p. The known kinematics of these mono-energetic particles allowed for an accurate calibration of the deuteron, $^3$He and $\alpha$-particle spectra. Triton spectra were assumed to have the same calibration as deuterons, which is reasonable in view of the fact that the $^3$He and alpha-particle energy calibrations were found to be identical. Figure 5-1 also shows the elastic peak for $^3$He + $^3$He scattering reduced by a factor of 50. The presence of this peak allowed a check on the energy calibration, and, by comparing the elastic yield to the previously measured elastic cross section, allowed a check on the cross-section measurements. The low-energy tail of the elastic peak, produced by slit scattering, is seen to contribute in the region of the $^3$He continuum, therefore a correction was determined by filling the cell with $^4$He gas and measuring the tail of elastically scattered $^3$He particles, there being no continuum $^3$He spectrum in this case. At very forward angles background produced by the cell window was measured by taking runs with the target cell evacuated.

Because of the large yield of elastic $^3$He particles there is some leakage into the $\alpha$-particle spectrum. This is seen in Fig. 5-1 as a sharp
peak in the $\alpha$-particle spectrum falling at the same pulse-height as the $^3$He elastic peak. This leakage contribution is easily subtracted from the $\alpha$-particle yield. The shelf appearing at the high energy end of the $\alpha$-particle spectrum, however, is real, being caused by the virtual state of the diproton.

Each particle spectrum was integrated from the maximum energy down to $E^*$ (in a few cases the instrumental cutoff of the spectrum was a few channels higher than $E^*$, so the spectrum was smoothly extrapolated to $E^*$). The resulting cross sections, labeled $\sigma^*_L$, are shown multiplied by $\sin \theta_L$ as a function of lab angle $\theta_L$ in Figs. 5-2 to 5-5 for the bombarding energy 21.7 MeV. The following procedure was adopted to extrapolate the angular distribution to $0^\circ$: $\sigma^*_L$ was plotted as a function of angle and a straight line was drawn through the data points at the three smallest angles; this straight line was extrapolated to $0^\circ$. Two other straight lines were drawn from the smallest angle data point to zero degrees, one of which intersected the ordinate at a value 50% larger than the original line, and the other at a value 50% less. When converted to a graph of $\sigma^*_L \sin \theta_L$ vs. $\theta_L$, these straight lines become the solid curves shown in Figs. 5-2 to 5-5. Particle production cross sections were then obtained by measuring the area under each of the distributions in these Figs. using the middle solid curve to extrapolate to zero degrees and using the calculated maximum angle $\theta_L^\text{max}$ to aid in extrapolating the large angle data smoothly to zero. For each particle, the production cross section is shown on the corresponding figure, where the major contribution to the quoted error is the uncertainty in the zero-degree extrapolation estimated by the area between the outermost solid curves.
Measurements similar to those at 21.7 MeV were taken at 17.9 MeV and at 24 MeV for deuterons and tritons alone. The results for the total particle production cross sections are shown in Fig. 5-6. One observes that the cross sections for production of deuterons and \(^3\)He particles are very nearly equal and about an order of magnitude greater than that for tritons. The \(\alpha\)-particle cross section, having a positive \(Q\)-value, is almost constant with energy.

From Eq. (4) the individual reaction cross sections are calculated and summarized along with the total reaction cross section in Table 5-2. Fig. 5-7 summarizes the total reaction cross section measurements. The solid dots are the present measurements; the point at 24 MeV is an estimate based on the measured triton and deuteron production cross section (see Fig. 5-6) and on extrapolating the almost constant \(\alpha\)-particle production cross section. This estimate further assumes that the cross section for the breakup of one \(^3\)He into two protons and a neutron and the cross section for the simultaneous breakup of each \(^3\)He into a proton and a deuteron are small. The crosses are the lower-energy unpublished data of Bacher. These data were obtained by measuring charge-1 particles only, and the symmetry about 90° was not made use of to minimize energy extrapolation errors. At 17.9 MeV there is a factor of two discrepancy between these data and the present work. It is possible that in Bacher's work elastically scattered \(^3\)He particles may have leaked into the charge-1 spectrum as the energy was raised. At his highest energy the charge-1 spectrum is dominated by a peak attributed to the diproton state. The magnitude of this peak is not consistent with the diproton contribution to our \(\alpha\)-particle spectrum at 17.9 MeV, and, furthermore it occurs at an energy near to where one
would expect that elastic $^3$He particles might leak in. We intend to investigate this discrepancy by measuring the proton spectrum at 17.9 MeV.

The solid triangles in Fig. 5-7 are the results of resonating group structure calculations made by Thompson et al. These calculations made use of a phenomenological imaginary potential, which at the lower energies, was adjusted to fit the data of Bacher. At the higher energies, the calculations were based on elastic scattering data only. There appears to be a discontinuity between Bacher's data and the higher energy calculations.

As soon as the discrepancy at 17.9 MeV between Bacher's data and the present work is investigated, measurements will be continued to higher energies and new resonating-group calculations will be made.

References


references concluded on p. 39.
Table 5-1. Q values (MeV) and lab threshold energies (MeV) for $^3$He + $^3$He reactions.

<table>
<thead>
<tr>
<th>Final State</th>
<th>Q</th>
<th>Threshold</th>
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</thead>
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<tr>
<td>2p$\alpha$</td>
<td>12.85</td>
<td>...</td>
</tr>
<tr>
<td>pd$^3$He</td>
<td>-5.50</td>
<td>10.98</td>
</tr>
<tr>
<td>3pt</td>
<td>-6.97</td>
<td>13.92</td>
</tr>
<tr>
<td>2pn$^3$He</td>
<td>-7.73</td>
<td>15.44</td>
</tr>
<tr>
<td>2p2d</td>
<td>-10.99</td>
<td>21.94</td>
</tr>
<tr>
<td>3pud</td>
<td>-13.23</td>
<td>26.39</td>
</tr>
<tr>
<td>4p2n</td>
<td>-15.46</td>
<td>30.84</td>
</tr>
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</table>

Table 5-2. Measured cross sections (mb) for $^3$He + $^3$He reactions at 17.9 and 21.7 MeV(lab).

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>17.9 MeV</th>
<th>21.7 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(2p\alpha)$</td>
<td>$112.6 \pm 4.4$</td>
<td>$114.3 \pm 4.7$</td>
</tr>
<tr>
<td>$\sigma(pd^3$He)</td>
<td>$41.8 \pm 4.4$</td>
<td>$129.5 \pm 9.1$</td>
</tr>
<tr>
<td>$\sigma(3pt)$</td>
<td>$0.6 \pm 0.1$</td>
<td>$6.5 \pm 1.0$</td>
</tr>
<tr>
<td>$\sigma(2pn^3$He)</td>
<td>$&lt; 4$</td>
<td>$&lt; 16$</td>
</tr>
<tr>
<td>$\sigma_R$</td>
<td>$152.3 \pm 6.5$</td>
<td>$250.0 \pm 14.1$</td>
</tr>
</tbody>
</table>
Fig. 5-1. Measured particle spectra from $^3$He bombardment by $^3$He at 21.7 MeV(lab).
Fig. 5-2. Energy-integrated cross section for triton production.

Fig. 5-3. Energy-integrated cross section for deuteron production.

Fig. 5-4. Energy integrated cross section for $\alpha$-particle production.

Fig. 5-5. Energy integrated cross section for $^3$He production.
Fig. 5-6. Measured total cross sections for production of d, t, α, and continuum $^3$He by the bombardment of $^3$He by $^3$He.


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**Fig. 5-7.** Total reaction cross sections for $^3\text{He} + ^3\text{He}$.  

- **$^3\text{He} + ^3\text{He}$**
- **X** THIS WORK
- **X** REF. 5
- **△** REF. 6
Because of the indistinguishability of the nucleons, the effective interaction between nuclei is rather complicated. The results of resonating-group calculations have indicated that this interaction consists of a long-range part which has an odd-even \( \ell \)-dependence and a short-range repulsive part. An examination of the behavior of the \( \alpha + \alpha \) system has shown that the repulsive part can be adequately represented by a "centrifugal-barrier-type" soft-core potential (Pauli core). Here we study further the utility of this particular type of core by applying it to the more complicated \( ^3\text{H} + ^4\text{He} \) system.

The effective potential between the \( ^3\text{H} \) and the \( ^4\text{He} \) clusters is written as

\[
V(r) = V_A(r) + V_R(r). \tag{1}
\]

From the discussion in Ref. 2, the repulsive part \( V_R \) is taken to be

\[
V_R(r) = \frac{\hbar^2}{2\mu r^2} \left[ N(N+1) - \ell(\ell+1) \right], \quad (r < r_{c\ell}) \\
= 0, \quad (r > r_{c\ell}) \tag{2}
\]

for \( \ell \leq 2 \), and is set equal to zero for \( \ell > 2 \). The value of \( N \) is taken to be 4 for \( \ell = 0 \) and 2, and 3 for \( \ell = 1 \). The part \( V_A \) is chosen to have an odd-even \( \ell \)-dependence; it is given by

\[
V_A(r) = C_e V_D(r), \quad (\ell = \text{even}) \\
= C_o V_D(r), \quad (\ell = \text{odd}) \tag{3}
\]
with $V_D(r)$ being the direct potential obtained by folding the direct part of the nucleon-nucleon potential into the matter-density distributions of the $^3\text{H}$ and $^4\text{He}$ clusters. The adjustable parameters contained in the potential $V(r)$ are the odd-even parameters, $C_o$ and $C_e$, and the cutoff radii $r_{c\ell}$. These parameters are varied at each energy to achieve a best fit with the results of the $^3\text{H} + ^4\text{He}$ resonating-group calculation obtained with a Serber interaction and with the exchange-Coulomb potential turned off.

The calculation with $V(r)$ shows that the cutoff radius $r_{c\ell}$ can be chosen as both energy- and $\ell$-independent. A good choice is $r_{c\ell} = 3.05$ fm, which should be compared with the corresponding value of about $2.80$ fm obtained in the $\alpha + \alpha$ case. Here one notes that the cutoff radius is about equal to the sum of the rms radii of the clusters involved, indicating that the repulsive effect arising from the Pauli principle is important only when the clusters begin to overlap.

The behavior of $C_o$ and $C_e$ is depicted in Fig. 6-1. One notes the following features: (i) Both $C_o$ and $C_e$ approach 1 as the energy becomes large. This is expected, because the Pauli principle should be less important at higher energies. (ii) $C_o$ is larger than $C_e$. This feature is not a universal one for the effective potential; for example, in the $d + ^4\text{He}$ case $C_e$ will be larger than $C_o$. (iii) The parameter $C_o$ is nearly energy-independent over a wide energy range, whereas the parameter $C_e$ varies rapidly with energy.

Differential cross sections are calculated at energies from 3 to 40 MeV. Because of the near constancy of $C_o$, we simply used
$C_0 = 1.319$ in this whole range. The results at 10 and 25 MeV are illustrated in Fig. 6-2, where the cross sections calculated with $V(r)$ (dashed curves) are compared with those from the resonating-group study (solid curves). As is seen, the agreement between these calculations is fairly good, indicating that the odd-even model with Pauli repulsive core is satisfactory in this problem.

Analogous calculations in the $d + ^4$He system also yield satisfactory results. Similarly, one can use this model to analyze heavier systems. For example, in the case of $\alpha + ^{16}$O scattering, one predicts that the cutoff radius will be equal to about 4 fm and that $C_e$ will be larger than $C_o$.

In conclusion, we feel that, even though this model is certainly not as refined as the resonating-group method, it is simple enough for a systematic analysis of many systems and can thereby yield further understanding about the importance of the Pauli principle in nuclear problems.

References
2. R. E. Brown, W. S. Chien, Y. C. Tang, in Proc. of Int. Conf. on Few Body Problems in Nuclear and Particle Physics, Quebec, 1974 (to be published); John H. Williams Laboratory of Nuclear Physics Annual Report, 1974, p. 21.
Fig. 6-1. $C_0$ and $C_e$ vs. energy.

Fig. 6-2. Comparison of calculated cross sections.
7. The Use of $\alpha+\alpha$ Scattering as a Selective Probe of the 
Nucleon-Nucleon Interaction

R. E. Brown

It has been suggested\(^1\) that analysis of the interaction $V_{\alpha\alpha}$ between two $\alpha$ particles can yield information on the direct part (that part of $V_{ij}$ depending only on $|\vec{r}_i - \vec{r}_j|$) $V_d$ of the nucleon-nucleon potential, and some attempts in this direction have recently been carried out\(^2-4\). The $\alpha+\alpha$ system has several characteristics which make it especially useful for such an investigation: (i) the first reaction threshold ($\alpha+\alpha \rightarrow p^7 Li$) occurs at a c.m. energy of 17.35 MeV, and therefore, an analysis of $\alpha+\alpha$ scattering in terms of a real potential can be carried out over a broad energy range, (ii) because the $\alpha$ particle has an isospin $I$ of 0 and a spin-parity $J^\pi$ of $0^+$, the nonexchange part $V_D$ of $V_{\alpha\alpha}$ arises mainly from $V_d$, (iii) exchange contributions\(^5-7\) to $V_{\alpha\alpha}$, caused by the operation of the Pauli exclusion principle, are of relatively short range and, in fact, can be neglected for $\ell \geq 4$, (iv) the $\ell=4$ phase shift increases by about 100° over the c.m. energy range 9 to 14 MeV\(^3\) and is therefore sensitive to $V_{\alpha\alpha}$ in this energy range. Items (ii) and (iii) suggest that from a rather simple potential-model analysis of the $\alpha+\alpha \ell=4$ phase shift $\delta_4$ one might be able to extract information on $V_d$ in a relatively straightforward manner. It is this possibility that is studied here.

From item (iii) above we may analyze $\delta_4$ by use of the direct contribution $V_D$ to $V_{\alpha\alpha}$ and may neglect exchange contributions. Thus
the potential $V$ of the Schrödinger equation for $\alpha+\alpha$ scattering ($\lambda \geq 4$) is written $V = V_D + V_C$, where $V_C$ is the Coulomb potential given by Eq. (11) of Ref. 3 and $V_D$ can be written [see Eq. (14) of Ref. 3]

$$V_D(r) = \int \rho(r_1)\rho(r_2)V_d(s)\delta\left(r_2-r_1-s+r\right)dr_1dr_2ds. \quad (1)$$

In Eq. (1) the $\alpha$-particle matter densities are of Gaussian form and are given by Eq. (16) of Ref. 3.

We proceed with the analysis by using for $V_d$, the direct part of the nucleon-nucleon potential, a function deduced from a recent treatment of the nucleon-nucleon interaction using a one boson exchange model (OBEM). From Table 7 it is seen that only exchange of mesons having $I=0$ and $J^\pi=0^+$ or $1^-$ contributes to $V_d$. Furthermore, Ref. 8 shows that the coupling strengths of the $\epsilon$ and the $\omega$ to the nucleon are much greater than those of the $S^*$ and the $\phi$. Therefore, in the present analysis we consider only $\epsilon$ and $\omega$ exchange as contributing to $V_d$. The contribution $V_{d\omega}$ to $V_d$ from $\omega$ exchange is given by

$$V_{d\omega} = g_{\omega}^2 h c \left[ \frac{m^2}{4M^2} + \frac{m_{\omega}^2}{2M_{\omega}} \right] \exp\left(-\frac{mc^2}{h}\right), \quad (2)$$

with $mc^2 = 783.9$ MeV, $M^2 = 938.905$ MeV, and $g_{\omega}/g_{\omega} = 0.637$. The situation on the $\epsilon$ meson is discussed in Refs. 3, 8, 10. Briefly, the $\epsilon$ seems to appear as an $I=0$, $s$-wave resonance in the $\pi\pi$ interaction and is several hundred MeV broad. Thus the expression for $V_{d\epsilon}$, the contribution to $V_d$ from $\epsilon$ exchange, involves an integration over the $\epsilon$ mass distribution $J(m)$. We take

$$V_{d\epsilon} = -g_{\epsilon}^2 h c \int_{2mc^2}^{\infty} J(m)\frac{1}{r} \exp\left(-\frac{mc^2}{h}\right) dr (mc^2), \quad (3)$$
with $2\mu c^2 = 269.929$ MeV ($\mu$ = pion mass) and

$$J(m) = \frac{2m_e c^2 r}{\pi} mc^2 f/\left[(m_e^2 - m_{\pi}^2)^2 + m_e^2 \Gamma^2 f^2\right],$$

with $f = \left\{ \frac{m_e^2 - 4\mu^2}{m_e^2 - 4\mu^2} \right\}^{1/2}$.

In Ref. 8 the mass and width of the $\pi$ were taken as $m_e^2 = 670$ MeV, $\Gamma = 500$ MeV, and for these values $J(m)$ is illustrated in Fig. 7-1.

On taking $V_d = V_{dw} + V_{de}$ we obtain from Eq. (1) $V_d = V_{dw} + V_{de}$, where $V_{dw}$ is given by Eq. (18) of Ref. 3, and the appropriate expressions for $V_d$ and $\beta$ of Ref. 3 can be deduced by comparing Eq. (2) above with Eq. (17) of Ref. 3. The expression for $V_{de}$ is

$$V_{de} = -16g_\pi^2 \hbar c \int \frac{J(m)}{2\mu c^2} r^{-1} \exp(-\beta r + 3\beta^2/(8\alpha))$$

$$\times \frac{1}{2} \left\{ 1 + \Phi(\lambda_-) - \exp(2\beta r)[1 - \Phi(\lambda_+)] \right\} d(mc^2),$$

where $\beta = mc/\hbar$, $\alpha = 0.514$ fm$^{-2}$ and is the $\alpha$-particle size parameter, $\Phi$ is the error function [Eq. (12) of Ref. 3], and $\lambda_+$ and $\lambda_-$ are given by Eq. (20) of Ref. 3.

Fitting to the $\lambda=4$ $\alpha+\alpha$ phase shifts$^{12}$ was carried out as follows. Values for $m_e$ and $\Gamma$ were fixed, and then the coupling constants $g_{\pi}$ and $g_\pi$ were varied to produce a least $\chi^2$ fit to $\delta_4$ vs c.m. energy $E$.

Very good fits to $\delta_4$ usually resulted, and a typical such fit to $\delta_4$ is shown in Fig. 7-2 along with the result for $\delta_6$ using the potential which produced the best fit to $\delta_4$. Figure 7-3 shows several best-fit values for $g_{\pi}$ and $g_{\pi}$. The circles and square are obtained from the present analysis with several different combinations of $m_e$ and $\Gamma$. The
point which is encircled gives the result found when the $m_e$ and $\Gamma$ 
values of Ref. 8 were used, and the triangle shows the result of 
Ref. 8 from fitting information on the nucleon-nucleon interaction. 
Because $V_{dw}$ is repulsive, we see that the $V_d$ of the nucleon-
nucleon potential of Ref. 8 is not as attractive as the $V_d$ we deter-
mine here from $\alpha+\alpha$ scattering. This is clearly illustrated in 
Fig. 7-4.

We also compare the present $V_d$ with direct parts of eight other 
nucleon-nucleon potentials from the literature $^{13-19}$. Figures 7-5 
and 7-6 show two of these comparisons. Comparisons with all the 
potentials are illustrated in Fig. 7-7 where the s-wave scattering 
length $a$ is shown; the more negative the value of $a$, the more 
attractive is the potential (i.e. the larger is the low-energy s-wave 
phase shift for nucleon scattering by $V_d$). The point labeled 8 
shows the present result, and this illustrates that the $V_d$ we derive 
is more attractive than the $V_d$ of any of the commonly used nucleon-
nucleon potentials. Some corrections to the present formulation of 
the $\alpha+\alpha$ analysis have been discussed in Refs. 1 and 3, but these are 
expected to produce only minor changes in the present results. It is 
more likely that the difficulty of the $\alpha+\alpha$ analysis producing a too 
attractive $V_d$ is associated with the short-range repulsive part in 
$V_d$ and the lack of allowance for short-range correlations in Eq. (1) 
of the present formulation $^{20}$. This lack results in the need for a 
too attractive $V_d$ in Eq. (1) in order to yield sufficient attraction 
in $V_D$ to properly reproduce $\delta_4$ vs $E$. Of course for this effect to 
be important, some of the nucleons in one $\alpha$ particle must come close
to some of those in the other during the collision. One might at first suppose that for $l=4$ the centrifugal barrier would prevent this from happening to any marked degree. However, it must be remembered that the present analysis covers an energy region where an $l=4$ resonance occurs, and therefore, the two $\alpha$ particles must overlap sufficiently to cause this resonance. This effect is illustrated in Fig. 7-8 where the $\alpha+\alpha$ nuclear plus centrifugal potential is plotted. The cross-hatched region of the potential indicates the region of significant $\alpha+\alpha$ interaction, and because the rms matter radius of the $\alpha$ particle is 1.48 fm (Ref. 21), it is seen that there is ample opportunity for nucleons in one $\alpha$ particle to come close to those in the other during the collision. It seems clear then that proper inclusion of short-range correlations in the analysis would bring the $V_d$ deduced from the $\alpha+\alpha$ interaction more into agreement with that yielded by the nucleon-nucleon potentials in common use. Such an inclusion is not simple, but some of the difficulties are currently being studied.

References

12. The $\xi=4$ phases used here are the same as used in Ref. 3.
20. Thanks are expressed to Y. C. Tang for discussions about this point.
TABLE 7-1. Some forms for the nucleon-nucleon potential from meson exchange. \( I \) is the isospin of the meson. An \( X \) indicates that exchange of the indicated meson contributes such a term to the nucleon-nucleon potential \( V_{ij} \).

<table>
<thead>
<tr>
<th>Meson</th>
<th>( J^\pi )</th>
<th>1</th>
<th>( \vec{c}_i \cdot \vec{\sigma}_j )</th>
<th>( S_{ij} )</th>
<th>( \vec{L} \cdot \vec{S} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon, s^* )</td>
<td>0(^+)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>( \eta )</td>
<td>0(^-)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>( \omega, \phi )</td>
<td>1(^-)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>( D )</td>
<td>1(^+)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meson</th>
<th>( J^\pi )</th>
<th>( \vec{\tau}_i \cdot \vec{\tau}_j )</th>
<th>( \vec{\tau}_i \cdot \vec{\tau}_j \vec{\sigma}_i \cdot \vec{\sigma}_j )</th>
<th>( \vec{\tau}_i \cdot \vec{\tau}<em>j S</em>{ij} )</th>
<th>( \vec{\tau}_i \cdot \vec{\tau}_j \vec{L} \cdot \vec{S} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta )</td>
<td>0(^+)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>( \pi )</td>
<td>0(^-)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>( \rho )</td>
<td>1(^-)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>( A_1, B )</td>
<td>1(^+)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 7-1. Mass distribution of $\epsilon$ meson from Eq. (4).

$\epsilon$ - meson mass distribution

$m_\epsilon c^2 = 670$ MeV

$\Gamma_\epsilon = 500$ MeV
Fig. 7-2. Fits to $\sigma+C$ phase shifts for $\ell=4$ and $\ell=6$.

Fig. 7-3. Coupling constants $g_\omega^2$ and $g_\epsilon$. 
Fig. 7-4. Present potential (αα) and that of Ref. 8 (OBEP).
Fig. 7-5. Present potential (\(\infty\)) and that of Ref. 13 (HJ).

Fig. 7-6. Present potential (\(\infty\)) and the soft-core potential of Ref. 17 (RSC).
Fig. 7 -7. s-wave scattering length $a$ for nucleon scattering from the direct parts only of nucleon-nucleon potentials. The labels 1-4 refer to the potentials of Refs. 13-16, respectively; the labels 5 and 6 refer to the hard-core and soft-core potentials, respectively, of Ref. 17; the labels 7 and 16 refer to the potentials of Refs. 18 and 19, respectively; and the label 8 refers to the present potential.

Fig. 7 -8. $\alpha+\alpha$ nuclear plus centrifugal potential.
8. Neutrons from the Bombardment of $^3\text{He}$ by Deuterons and Protons

C. H. Poppe, J. C. Davis *, J. D. Anderson *, S. M. Grimes * and C. Wong *

Continuous neutron spectra produced by bombarding $^3\text{He}$ with deuterons and protons have been measured at a variety of energies and neutron emission angles using the cyclograaff accelerator of the Lawrence Livermore Laboratory. Deuteron-induced spectra were measured at bombarding energies of 12, 14, 16 and 19 MeV while spectra produced by proton bombardment were measured at 22 and 25 MeV. The energy of the emitted neutrons was measured using pulsed-beam time-of-flight spectrometry.

$^3\text{He}$ gas of 99.99% purity at a pressure of 1 or 2 atm. was contained in a 7.6 cm diameter cylindrical gas cell with a 6 μm Havar foil window located at the center of an evacuated, thin-wall stainless steel scattering chamber. The neutron detectors were sixteen NE213 liquid scintillators mounted in holes in the concrete shield wall 10.8 m from the target behind 1 m-long water-filled collimators. The detector-collimator combinations are spaced about 7.5° apart at forward angles and 15.5° apart at back angles, covering the angular range from 3.5° to 159°. This geometry prevents the detectors from viewing either the beam collimators or beam dump, so that in conjunction with the massive concrete shielding, neutron background may be kept to a minimum. Gamma-rays are largely eliminated by standard pulse-shape discrimination techniques. Time-of-flight spectra were collected in all detectors simultaneously, although only the more forward angle spectra were useful. Suppression of every other stop
pulse allows a double display to be accumulated so an accurate time
 calibration may be made from the location of the prompt target γ ray
 peak and its mate one period later which leak through the pulse
discrimination circuit.

For the deuteron runs a substantial neutron background was
produced by the Havar foil so that background runs were taken with
the cell evacuated. Fig. 8-1 shows the results at the forward-
most angle, where the differential-cross section for the production
of neutrons of energies between E and E + dE is plotted as a function
of neutron energy in the laboratory system. Data points are shown
for the 19-MeV data only, where the error bars reflect statistical
errors--there is, in addition, a 7% scale error because of uncertainty
in the absolute efficiency of the neutron detectors. Smooth curves
were drawn through the data at all energies in order to illustrate
the trend.

The arrows labeled "3" indicate for each incident energy the
maximum possible energy of neutrons from deuteron breakup which pro-
duces 3 particles in the final state. Above a bombarding energy of
12.87 MeV the ³He nucleus can break up also. The maximum energy for
this 4-body final state is shown, for 19 MeV only, by the arrow
labeled "4". Complete breakup of both projectile and target is
possible above 16.58 MeV and for the 19 MeV spectrum neutrons of
maximum possible energy would occur at the arrow labeled "5".

This reaction has been studied between 7 and 12 MeV by Kerr¹
and agreement between his 12 MeV spectrum at 0° and these data is
quite good, with the exception that the better time resolution used
in this experiment yields a steeper rise on the high energy side of
the spectrum and no neutrons are observed at energies greater than
the maximum possible energy. As in the case of Kerr's data the
spectra obtained at small angles are characterized by a prominent
peak.

Fig. 8-2 shows the trend of the 19 MeV data as a function of
neutron laboratory angle. The angles are 3.5°, 9.2°, 16.7°, 23.8°
and then increasing in about 7.5° steps out to 61.4°. Data points
are shown for 3.5°, 23.8° and 61.4°, the detectors at the latter 2
angles have 5x the area of the others which accounts for the improved
statistical accuracy. The yield of neutrons is very forward peaked
in the laboratory and the prominent maximum in the energy spectrum
has disappeared by about 24°.

Fig. 8-3 shows similar results at a deuteron bombarding energy
of 14 MeV. Again, the spectra are for 3.5, 9.2, 16.7, 23.8° and on
out to about 100°. A lower detector bias was used at this bombarding
energy than for the 19 MeV data which accounts for the ability to
reach somewhat larger angles. The yield is again strongly peaked in
the forward direction, although not as much as at 19 MeV, and the
prominent maximum in the spectrum appears to persist to larger angles.

As was found in the lower energy work of Kerr, these spectra
exhibit no narrow peaks, comparable to the one observed in deuteron
breakup on tritium, which is to be expected on the assignment of
T = 0 to the excited states of the α-particle lying below about 25
MeV. From the phase shift analysis by Tombrello of p + 3He
scattering the ground state of 4Li, which is unbound, is assigned
$J^\pi = 2^-$ and occurs about 4.7 MeV above the mass of $p + ^3\text{He}$. The existence of this broad $T = 1$ state—the ratio of its width to the Wigner limit is 1—could possibly account for the prominent maximum in these neutron spectra. However, the predicted position of a peak from the Q-value for this state is not consistent at all with the location of the maximum in the neutron spectra. This is especially true for the lower energy data of Kerr, where for most of his energies the state in $^4\text{Li}$ cannot be reached energetically. For the higher energy data presented here the location of the maximum in the neutron spectra is closer to where one would expect a peak due to the $^4\text{Li}$ ground state, but the maximum in the data still occurs at a neutron energy 1 to 2 MeV too high. In fact, for these data no consistent Q-value can be extracted from the location of the maximum. Because the state in $^4\text{Li}$ is very broad any arguments based just on the location of maximum are suspect and one should perform calculations, for example using the Watson-Migdal approach, to take into account the final state interaction between the proton and the $^3\text{He}$ nucleus. This has been reported to be successful at lower energies using Tombrello's phase shifts.

Other mechanisms which would enhance the spectra at certain neutron energies are final state interactions and two-step processes. If a p-n final state interaction through the virtual state of the deuteron were to occur, the neutron spectrum would be enhanced at the energy corresponding to the proton and neutron emitted at the same angle with very small relative velocity. Kerr shows, for his 10-MeV zero degree spectrum, that the location of the maximum is not
inconsistent with this picture, however, as one goes to higher energies the location of a peak due to a p-n final state interaction occurs at lower and lower neutron energies relative to the observed maximum, differing by 2.5 MeV at a bombarding energy of 19 MeV. The two-step process whereby $^4\text{He}$ is formed in an excited state which subsequently decays by neutron emission could produce peaks in the neutron spectrum whose shape depends on the width of the intermediate state. With the exception of the first excited state which is below the $n + ^3\text{He}$ threshold, the excited states of $^4\text{He}$ are generally quite broad. Furthermore, at 19 MeV, where the maximum in the neutron spectrum is most prominent, none of these states could produce an enhancement at the right neutron energy.

Rybakov et al. attempted to explain the deviation of the $^0\text{d} + ^3\text{He}$ neutron spectrum at 19 MeV from a simple phase-space distribution by taking into account the formation of particle pairs of non-zero angular momentum. However, a similar calculation at 10 MeV by Kerr did not fit his data.

It thus appears that there is no simple explanation of the observed shape of the neutron spectrum from deuterons bombarding $^3\text{He}$ and that perhaps several mechanisms are responsible. The relative importance of each mechanism may change as a function of bombarding energy.

The production of neutrons by the proton induced breakup of $^3\text{He}$ is shown in Fig. 8-4. The data are for an incident energy of 25 MeV and the experimental procedure was identical to that described for the previous reaction, with the exception that the target cell was filled with $^4\text{He}$ for the background runs. Here the cross section is about 2
orders of magnitude less than that for the $d + ^3He$ experiment and the statistical errors are correspondingly worse. Data points are shown for $3.5^\circ$ and the arrow labeled "4" indicates the maximum possible neutron energy for breakup into the 4-particle final state. A smooth curve is drawn through the data to guide the eye and similar curves are shown for $9.2, 16.7, 23.8^\circ$ and on out to $46^\circ$. Spectra obtained at a bombarding energy of 22 MeV were similar although of smaller cross section. For both cases the yield is not as forward peaked as for $d + ^3He$. None of the spectra show any peaks which could correspond to the formation of a triproton.

This reaction has been observed previously by Bacher et al. at 24.9 MeV and a neutron emission angle of $8^\circ$ using a proton recoil spectrometer. The data presented here are in reasonable agreement with theirs. We are, however, able to lower the minimum neutron energy observed by about 3 MeV compared to their work. They report that their data are in disagreement with the prediction of a 4-body phase space distribution and suggest that a $^1S_0$ final-state interaction between 2 protons is responsible.

References

*Lawrence Livermore Laboratory


5. W. E. Meyerhof and T. A. Tombrello, Nucl. Phys. A109, 1 (1968). See discussion about reaction \(^3\text{He}(d,n)^3\text{He} + ^1\text{H}.


Fig. 8-1. Laboratory energy spectra at 3.5° for neutrons from $D + ^3\text{He}$ for bombarding energies of 12, 14, 16 and 19 MeV.

Fig. 8-2. 19-MeV laboratory energy spectra for neutrons from $D + ^3\text{He}$ as a function of angle.
Fig. 8-3. 14-MeV laboratory energy spectra for neutrons from D + ³He as a function of angle.

Fig. 8-4. 25-MeV laboratory energy spectra for neutrons from p + ³He as a function of angle.
II. INELASTIC MONOPOLE TRANSITIONS AND MICROSCOPIC ANALYSIS OF INELASTIC SCATTERING

9. Shell Structure Information From Monopole Transitions in α Scattering From $^{24}$Mg and $^{28}$Si

H. P. Morsch, D. Dehnhard and T. K. Li

Inelastic monopole transitions are suited for a detailed study of n particle-n hole configuration mixing in the nuclear ground state and excited $0^+$ states. We completed the study of such transitions in inelastic α scattering from $^{24}$Mg and $^{28}$Si. To measure the deep minima in the $L = 0$ angular distributions (see Fig. 9-1) special care had to be taken in beam focusing to reduce spectral background. A microscopic model was used to analyse the data.

This is discussed in detail in ref. 2. In addition to large contributions from $(d_{5/2}^{-n}s_{1/2}^{n})$ and $(d_{5/2}^{-n}d_{3/2}^{n})$ components [in brief $(d_{5/2}^{-s_{1/2}})$ and $(d_{5/2}^{-d_{3/2}})$] we found contributions from $(p_{1/2}^{-d_{5/2}})$ components in the wave function of the $0^+$ states. In Fig. 9-2 the sensitivity of our calculation to the different n particle-n hole structures is demonstrated. The dashed line which shows a very little structure refers to a pure $(d_{5/2}^{-s_{1/2}})$ configuration. By including sizable $(d_{5/2}^{-d_{3/2}})$ components the structure is not significantly changed. Only by including $(p_{1/2}^{-d_{5/2}})$ components the very pronounced structure is obtained. The different curves are normalised to give the same cross section at about $20^\circ$. E0 matrix elements were derived from our spectroscopic results which are in excellent agreement with those obtained from electron scattering (see ref. 2).
Fig. 9-1. Inelastic $\alpha$-scattering from $^{24}\text{Mg}$ and $^{28}\text{Si}$. 
References


Fig. 9-2. Inelastic C-scattering from $^{24}$Mg, showing the sensitivity of the calculation to different particle-hole structures. Curves are normalized at 20°.
10. **A Search for Inelastic Monopole Transitions in Odd-$A$ Nuclei**

H. P. Morsch, J. L. Artz, D. Dehnhard, and T. K. Li

In a systematic study of inelastic monopole transitions we searched for such $L = 0$ transitions in odd $A$ nuclei. Generally these transitions are not necessarily expected if the selection rules allow transitions of higher multipolarity. Only if the states involved have a particular structure, specifically a "monopole structure", would inelastic monopole transitions be observed.

Specific odd $A$ nuclei included in our search were $^{27}\text{Al}$ and $^{29}\text{Si}$. For $^{29}\text{Si}$, the transition from the $1/2^+$ ground state to the first excited $1/2^+$ state at 4.84 MeV can be considered a trivial case in our search because only $L = 0$ is allowed. This is not the case, however, for $^{27}\text{Al}$ since the $5/2^+$ ground state can couple with a particular $5/2^+$ excited state with multipolarities of not only $L = 0$ but also $L = 2, 4$.

The experiments were performed using $^3\text{He}$ and $\alpha$ beams from the MP Tandem. Scattered particles were detected by position sensitive detectors in the focal plane of the Enge Split-Pole spectrometer. Initially $\alpha$ scattering from $^{27}\text{Al}$ was measured. However, deeply structured angular distributions similar to that reported previously$^1$ for $^{28}\text{Si}$ were not found. In Fig. 10 -1 the angular distribution of the transition to the 4.81 MeV state of $^{27}\text{Al}$ is shown in comparison with that of the monopole transition to the 4.98 MeV state in $^{28}\text{Si}$. The fact that an angular distribution without deep minima is observed in $\alpha$ scattering from $^{27}\text{Al}$ may be partially due to compound nuclear
contributions which are much stronger for the case in which the initial and final state has $J^\pi = 5/2^+$ than for that case in which $0^+$ states are involved. Because compound nuclear effects are known to be less important when $^3$He projectiles are used, we decided to study the inelastic $^3$He scattering to the same states.

In Fig. 10-2 angular distributions are shown for the $^3$He induced excitation of the $0^+$ state at 4.98 MeV in $^{28}$Si and the $1/2^+$ state at 4.84 MeV in $^{29}$Si. The angular distributions are very similar and have a characteristic $L = 0$ shape very different from transitions of higher multipolarity. Such higher multipolarity transitions are illustrated in Fig. 10-3 for excitation of the $2^+$ and $4^+$ states in $^{28}$Si. Hence an $L = 0$ assignment for the transitions in Fig. 10-2 is rather unambiguous. Also shown in Fig. 10-3 are the measured angular distributions for the excitation of low lying $5/2^+$ states in $^{27}$Al. The angular distribution to the lowest $5/2^+$ excited state at 2.73 MeV shows a dominant $L = 2$ shape. However, a slightly different shape is found when compared to the other $L = 2$ transitions to the $1/2^+$, $3/2^+$, $7/2^+$ and $9/2^+$ states which have angular distributions almost identical to that of the $2^+$ state in $^{28}$Si (see section 11). In addition to coupled channel effects this difference in shape may be due to a small monopole contribution. The angular distributions for the 3.96 and 4.41 MeV states show unstructured angular distributions, the latter similar in shape to that for the $4^+$ state in $^{28}$Si. Finally the angular distributions for the excitation of the states at 4.81 and 5.25 MeV show a pronounced structured very similar to that for the monopole transition to the $0^+$ state in $^{28}$Si which indicates the monopole character of these transitions.
The fact that a dominant monopole character was observed implies that the structure of these states may be described by configuration mixing of deformed states with the basic shell model state. This also means that the contributions from particle-hole excitations to the transitions are small. Particle-hole excitations within the (sd) shell can give rise only to quadrupole or hexadecapole transitions. Further we find summed monopole excitation strengths (Table 10-1) which are comparable for the odd A nuclei $^{27}$Al, $^{29}$Si and the even nucleus $^{28}$Si. These results indicate that, first, the monopole strength for $^{27}$Al is concentrated in the states at 4.81 and 5.25 MeV. Secondly, since monopole and quadrupole transitions are trivially separated for even nuclei and since the same relative strengths are observed for both even and odd nuclei, we conclude that the mixing of monopole and quadrupole transitions in odd A nuclei is also small. This conclusion may be understood by the very different structure of n particle-n hole configuration mixing as compared with lph excitations.

Reference

| Table 10-1. Summed Transition Amplitudes Relative to $^{28}$Si. |
|-----------------|-----------------|-----------------|
|                | $^{27}$Al       | $^{28}$Si       | $^{29}$Si       |
| E0              | 90%             | 100%            | 77%             |
| E2              | 85%             | 100%            | 89%             |
Fig. 10-1. Comparison of transition to the 4.81 MeV state in $^{27}$Al with transition to the 4.98 MeV state in $^{28}$Si.
Fig. 10-2. Comparison of angular distributions for the inelastic scattering of $^3$He leading to the $D^+$ state at 4.98 MeV in $^{28}\text{Si}$ and the $1/2^+$ state at 4.84 MeV in $^{29}\text{Si}$. 

Inelastic $^3\text{He}$ Scattering
$E_{^3\text{He}} = 25.0$ MeV
Fig. 10-3. Excitation of $2^+$, $4^+$ and excited $0^+$ states in $^{28}\text{Si}$ and low lying $5/2^+$ states in $^{27}\text{Al}$. 
In the search for monopole transitions on odd-A nuclei discussed in the previous article, additional inelastic $^3$He scattering data were obtained for many other low lying states of $^{27}$Al and $^{29}$Si. Part of this data, illustrated in Fig.11 -1, shows angular distributions which exhibit dominant $L = 2$ structure. For $^{27}$Al the excited states shown are the members of the proposed $^{28}$Si$(2^+)$×$(1d\ 5/2)^{-1}$ quadrupole multiplet. For $^{29}$Si a $^{28}$Si$(2^+)$×$(2s\ 1/2)^{1}$ structure would give rise to one $3/2^+$ and one $5/2^+$ state. Experimentally, we find two $3/2^+$ states of comparable strength at 1.27 and 2.43 MeV. Similar splitting of excitation strength to $5/2^+$ states is not observed. The second $5/2^+$ state at 3.07 MeV is very weakly excited and has no typical $L = 2$ structure.

Preliminary DWBA calculations using microscopic radial form factors are shown in Fig.11 -1 and give good fits to the data. Spectroscopic strengths derived from the absolute cross sections are being determined. The summed $L = 2$ strengths for both $^{27}$Al and $^{29}$Si are compared with the $L = 2$ strength for excitation of the first $2^+$ state in $^{28}$Si in Table10 -1 (of the previous article). Similar to the summed monopole strengths, we find comparable strengths for the quadrupole transitions.
Fig. 11-1. Inelastic $^3\text{He}$ Scattering From $^{27}\text{Al}$ and $^{29}\text{Si}$ at 25 MeV.
Microscopic Coupled Channel Study of Inelastic $^3$He Scattering from $^{24}$Mg

H. P. Morsch, D. Dehnhard, A. Dudek-Ellis and P. J. Ellis

For inelastic $^3$He scattering from $^{24}$Mg to the $2^+(1.37$ MeV) and $4^+(4.23$ MeV) states a coupled channel calculation was performed in which a microscopic description of the transition form factor is used. The coupled channel code INCH was modified for the use of external form factors. A search routine allows the refitting of the optical parameters. Two different microscopic descriptions were used for the transition form factors, first a shell model description using a renormalization of the effective interaction due to core polarization. Similar to ref. 1 simple valence particle wave functions were used, in this case a simple $(d_{5/2})^{-4}$ structure. To reproduce the experimental $B(E2)$ value for the $0^+ - 2^+$ transition with this wave function an effective charge of $e_p + e_n = 4.7$ is necessary. In the second description an SU$_3$ representation of the nuclear wave functions was employed. Using a pure $[4] (80)$ representation which implies $S = T = 0$ only a small effective charge of $e_p + e_n = 2$ is needed.

Of particular interest is the question as to whether the flat $4^+$ state angular distribution in $^3$He scattering can be described. The results of our calculations with the $(d_{5/2})^{-4}$ form factor are shown in Fig. 12 -1 together with the experimental data. A good fit to the data is obtained for the $0^+$, $2^+$ and also for the $4^+$ angular distribution. For excitation of the $2^+$ state a renormalized effective interaction of 55.5 MeV has been used which is very close to the average value of
50.9 MeV found for heavier (sd) and f$_{7/2}$ shell nuclei. Using the same interaction the experimental strength of the 4$^+$ state transition required an extra enhancement factor of 1.16 for the 2$^+$ $\rightarrow$ 4$^+$ transition with respect to the 0$^+$ $\rightarrow$ 2$^+$ transition. This corresponds to an effective charge $e_p + e_n = 5.5$ which is in qualitative agreement with a value of 6.8 required to fit the experimental B(E2) value for the 2$^+$ $\rightarrow$ 4$^+$ transition. In addition a relatively small direct 0$^+$ $\rightarrow$ 4$^+$ L = 4 contribution was needed whose strength is close to the single particle value. If a volume integral of the effective nucleon-nucleon interaction of 446 MeV fm$^3$ is used this 0$^+$ $\rightarrow$ 4$^+$ matrix element is enhanced only by a factor of 1.3. Thus, hexadacapole effective charges are not greatly enhanced from the bare values.

In Fig. 12-2 the coupled channel effects are shown for the 0$^+$ and 2$^+$ state. The solid lines refer to our final result, the dashed lines represent a calculation using the optical potentials from a simple optical model analysis of elastic scattering (see Table 1). For the angular distributions of the 0$^+$ and 2$^+$ states the coupling to the 4$^+$ state and reorientation effects are found to be small. In Fig. 12-3 the different contributions for the excitation of the 4$^+$ state are shown. Also for this transition reorientation contributions are small. The pure 0$^+$ $\rightarrow$ 4$^+$ L = 4 excitation shows quite a pronounced structure very different from that of the two step contributions which allowed an estimate of the relative single step L = 4 and two step L = 2 transition strength. The L = 4 contribution (via 2$^+$ $\rightarrow$ 4$^+$) to the two step excitation of the 4$^+$ state is shown by the dot-dashed line. It has negligible strength. A DWBA calculation gives a very
similar result to the direct $0^+ - 4^+$ excitation whose shape is in disagreement with the data.

The calculation using the SO wave function shows the following result: In spite of the complicated shell model structure and the fact that also $(d_{5/2} - s_{1/2})$ matrix elements contribute, the structure of the $2^+$ angular distribution is very similar to that obtained in the description discussed above. The extra enhancement factors for the $2^+-4^+$ matrix element is nicely reproduced in the SU$_3$ model yielding a $B(E2)$ value for the $2^+-4^+$ transition of $125 e^2 fm^4$ compared to the experimental value of $98 \pm 18 e^2 fm^4$. However, the SU$_3$ model is designed to include quadrupole effects and it is found that the $0^+-4^+$ matrix element is very weak. To achieve the strength in Fig.12-3 an enormous enhancement would be required. It does seem that a non-zero $0^+-4^+$ contribution is needed for which the pure SU$_3$ wave functions are inadequate.

Conventional coupled channel calculations using complex collective form factors are underway and a comparison of the microscopic and macroscopic calculations should be interesting.

References

2. D. Dehnhard and N. S. Chant, Williams Laboratory Annual Report 1971, p.58

Table 12-1. Optical Parameters

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Fig. 12-1. Elastic and Inelastic Scattering of $^3\text{He}$ on $^{24}\text{Mg}$. Dots are experimental; lines are calculated using parameters described in the text.
Fig. 12.2. Elastic and Inelastic Scattering of $^3$He on $^{24}$Mg Showing Coupled Channel Effects. Solid lines are final result; dashed lines are calculated using simple optical model potentials listed in Table 12-1.
Fig. 12-3. Inelastic scattering of $^3$He on $^{24}$Mg showing the different contributions for the excitation of the $4^+$ state.
13. Collective Quadrupole Transitions in a Shell Model Description
In a microscopic description in which many lplh core polarization components are taken into account explicitly. In this description no effective charges are used. Effective interactions are used which are consistent with interactions describing few nucleon problems.

The excitation of low lying quadrupole states is discussed in $^3\text{He}$ and $\alpha$ scattering but also in heavy ion scattering which shows features markedly different from light ion scattering.

The nuclear wave functions were used in the form:

$$|0^{+}\text{gs}\rangle + a_1 |\text{val}\rangle + \sum_{k_n} b_{ik_n} |p_{h}^{n}\rangle_{k_n}$$

$$|2^{+}\rangle = a_1 |\text{val}\rangle + \sum_{k_m} b_{ik_m} |p_{h}^{m}\rangle_{k_m}$$

$$+ \sum_{k} b_{ik} |lplh(\text{val})\rangle_{k} + \sum_{k_{\nu}} b_{ik_{\nu}} |lplh(p^{\nu}h^{\nu})\rangle_{k}$$

where $|\text{val}\rangle$ is the valence-particle configuration in the lowest unfilled orbit and $|p^{\nu}h^{\nu}\rangle$ are particle-hole components with respect to $|\text{val}\rangle$; $|lplh(x)\rangle$ are $2\hbar\omega$ quadrupole excitations (in an oscillator notation) of the different configurations $x$.

In the following it is assumed that in addition to the (lplh) excitations the low lying $2^+$ state is described by $|\text{val}\rangle$ only. Using a more complex shell model structure e.g. in the $f_{7/2}$ shell where (fp) components are considered, the $(f_{7/2})^n$ component is still dominant.
Even if this would not be the case it would not affect these calculations, because the valence-particle excitation yields only a small fraction of the excitation strength. Further, the (lplh) amplitudes $b_{ik}$ and $b_{ik'}$ are replaced by average amplitudes $\bar{b}_i$. This is justified by the large number of (lplh) components e.g. 35 components in the sum over $k$ in the case of $^{44}$Ca. This assumption was tested by using different arbitrary weights for the lplh excitation e.g. changes of less than 10% have been obtained by using $b_{ik} = \frac{5_i}{\langle M_L \rangle_k}$ where $M_L$ are angular momentum matrix elements which change up to a factor of five between different components. With this assumption the transition matrix elements become:

$$\langle 2^+ \text{coll} | \mathcal{V} | 0^+ \text{gs} \rangle = a_2 a_1 \langle \text{val} | \mathcal{V} | \text{val} \rangle + b_2 \sum_k \langle \text{lplh}(0^+ \text{gs}) | \mathcal{V} | 0^+ \text{gs} \rangle_k \quad (3)$$

$$\langle \text{GQR} | \mathcal{V} | 0^+ \text{gs} \rangle \approx \bar{b}_3 \sum_k \langle \text{lplh}(0^+ \text{gs}) | \mathcal{V} | 0^+ \text{gs} \rangle_k \quad (4)$$

In eq. (3) and (4) the excitation of the low lying collective state and the GQR have essentially the same features. By a comparison with experimental data the average (lplh) amplitudes $\bar{b}_2$ and $\bar{b}_3$ can be estimated if good information about the ground state wave functions are available. In the mass region of interest only for $^{40}$Ca are shell model wave functions available in which a sufficient number of n particle-n hole components are included to account at least qualitatively for the experimental data on configuration mixing of the lowest $0^+$ states.

Experimental information on the configuration mixing of the target ground state can be obtained by measuring monopole transitions
in the scattering of charged particles or from $e^+e^-$ pair production. The derived monopole transition amplitudes or monopole matrix elements are approximately proportional to the sum of n particle-n hole amplitudes $\sum_{k_n} b_{k_n}$ and can be used to simplify the lplh matrix elements. By replacing the lplh form factor of the $(p^n h^n)$ components by that of the valence particle component (which differs for wave functions by less than 3%) this leads to

$$\langle lplh(0^+gs) | V | 0^+gs \rangle_k \sim (a_1 + MO) \langle lplh(val) | V | val \rangle_k .$$

MO is the sum of particle-hole amplitudes (eg. in ref. 1).

Eq. (5) implies a strong correlation between monopole matrix elements and the excitation strength of the collective $2^+$ state. Such a correlation has been found experimentally and may account for the observed shell effects in the excitation of low lying quadrupole states. So far, only few experimental data are available on monopole transitions, therefore often only the amplitude $b^{*}_i = b_i (a_1 + MO)$ can be extracted from the experimental data. For the effective interaction a nucleon-nucleon interaction of Gaussian form was used with a range of 1.68 fm and a volume integral of 446 MeV fm$^3$; which is consistent with interactions describing few nucleon problems. For $^3$He and $\alpha$ scattering this was folded with Gaussian $^3$He and $\alpha$ internal wave functions of ref. 3, for heavy ion scattering this was folded with electron densities. Details of the present calculations are similar to those of refs. 4.

1. **Excitation of the low lying quadrupole state in $^3$He and $\alpha$ scattering**

Because monopole transition amplitudes are available for $^{44}$Ca (ref. 1) microscopic calculations were performed for the excitation of the first excited $2^+$ states in $^{44}$Ca in $^3$He and $\alpha$ scattering. For
the valence particle component a simple \((f_{7/2})^4\) configuration is used. Fig. 13-1 shows inelastic form factors for the \((f_{7/2})^4\) and the lplh component. Also the orbits included in the lplh calculation are shown schematically. Compared to the \((f_{7/2})^4\) form factor the lplh form factor extends to larger radii leading to a transition radius of 4.74 fm which is in excellent agreement with results from electron scattering. No change of the usual bound state geometry \((r_0 = 1.25 \text{ fm}, a = 0.65 \text{ fm})\) was necessary to attain the large transition radius. Excellent fits to the experimental data in Fig. 13-2 are obtained with the lplh amplitudes \(b_2\) of 0.087 for \(^3\)He scattering and of 0.073 for \(\alpha\) scattering. To reproduce the \(B(E2)\) value a \(b_2\) value of 0.084 is required. These results show that by using the same lplh amplitudes for both the electromagnetic transition and the inelastic scattering the data are well reproduced, although the effect of core polarization yields a much larger enhancement factor for inelastic scattering (see section 31).

2. Excitation of the Giant Quadrupole Resonance

Calculations for the excitation of the GQR are performed for \(\alpha\) scattering from \(^{40}\)Ca (Fig. 13-3) and \(d\) scattering from \(^{58}\)Ni (Fig.13-4). The lplh calculation includes 32 components for \(^{40}\)Ca and 46 components for \(^{58}\)Ni. Excellent descriptions of the data are obtained (solid lines in Fig. 13-3 and 13-4) using lplh amplitudes \(b_3^*\) of 0.198 for \(^{40}\)Ca and \(b_3^*\) of 0.144 for \(^{58}\)Ni (corrected to the same number of lplh components as for \(^{40}\)Ca would give 0.20 which is very close to that found for \(^{40}\)Ca).
In the past the Giant resonance observed in inelastic scattering was also discussed in terms of a monopole excitation (breathing mode), and therefore in Fig. 13-3 and 13-4 differential cross sections are also shown by the dashed lines using the monopole estimate of ref. 4. In α scattering the monopole calculation exhibits a very pronounced structure and gives a cross section limit which is much smaller than the experimental data. Different features are seen in the d scattering. The absolute cross section of the monopole estimate is close to the experimental data, however, the structure of the monopole calculation does not fit the experimental data. These results confirm the assignments of an underlying quadrupole excitation.

3. Inelastic heavy ion scattering

The present lplh calculation was also applied to our experimental data on 18O scattering from 48Ca, 54Fe and 58Ni (see section 31). For the valence particle components a \( (f_{7/2})^{-2} \) component was used for 54Fe and a \( (p_{3/2})^{2} \) component for 58Ni. For these strong transitions in 54Fe and 58Ni lplh amplitudes were determined by fitting \( B(E2) \) values. This yields \( b_{2}^{*} = 0.172 \) for 54Fe and \( b_{2}^{*} = 0.184 \) for 58Ni. Using these components for both the proton and neutron components in the inelastic 18O scattering yields an excellent description of the inelastic cross sections (solid lines in Fig. 13-5). Different from 54Fe and 58Ni, for 48Ca recoupling matrix elements which are only due to n particle-n hole configuration mixing are very small. From electron scattering a lplh amplitude \( b_{2} \) of 0.0965 is obtained. Using this amplitude also for all possible neutron particle-hole excitations gives a good description of the experimental data (Fig. 13-5).
Although in all cases the absolute cross sections are well reproduced, for the $^{54}$Fe and $^{58}$Ni excitations the data are not fitted in the nuclear Coulomb interference region. This may be due to coupled channel effects.

Finally the results of the lplh calculation (solid lines in Fig. 13-5) are compared with the simpler shell model description discussed in section 3I (dashed lines in Fig. 13-5). A very close agreement is obtained for the two different descriptions. It should be noted that in the simpler shell model description the effective interaction is dependent on the shell model wave functions used. If simple valence particle wave functions are used then an interaction is required with an extended range. This is because the valence particle wave functions give a transition radius much smaller than the experimental value. This is compensated by an extended range of the effective interaction of 2.06 fm compared to a value of 1.68 fm used in the lplh calculation which is consistent with interactions describing few nucleon systems.

References
Fig. 13-1. Inelastic form factors for the $(f_{7/2})^4$ and $lplh$ components for excitation of the first excited $2^+$ states in $^{44}$Ca by $^3$He scattering. The orbits included in the $lplh$ calculation are shown schematically.
Fig. 13-2. Inelastic scattering of $\alpha$ and $^3$He on $^{44}$Ca. Dots are experimental; lines calculated using parameters described in the text.
Fig. 13-3. α-particle scattering from $^{40}$Ca. Dots are experimental; solid line, lplh calculation; dashed line, monopole calculation.
Fig. 13-4. Deuteron scattering from $^{58}\text{Ni}$. Dots are experimental; solid line, lplh calculation; dashed line, monopole calculation.

$^{58}\text{Ni} + d$
$E_d = 70.3$ MeV

GQR
$E_x = 16$ MeV
Fig. 13-5. Comparison of lplh calculation (solid lines) with shell model calculation (dashed lines).
One of the difficulties encountered in the analysis\textsuperscript{1} for $^{28}\text{Si}(\alpha,\alpha')^{28}\text{Si}^*$ (1.78 MeV, $2^+$) is the strong variation of cross sections with bombarding energy. For instance, the $6^o$(Lab) cross sections vary by almost a factor of two over the energy range from $E_{\text{Lab}} = 23$ to 25 MeV. Angular distributions taken at three bombarding energies had significantly different cross sections but exhibited deep minima and similar shapes. The fact that these angular distributions are strongly structured and that their shapes do not vary much with energy allows an explanation involving major compound nuclear contributions to the inelastic cross sections to be unlikely. Considering previously discussed\textsuperscript{1} reaction thresholds in this energy interval, we suggest that the absorptive potential in the optical model parameterization of the distorted waves might account for the changing reaction cross sections.

In order to allow simultaneous fits to elastic and inelastic scattering by a coupled channels computer code, we have measured elastic $\alpha$ scattering on $^{28}\text{Si}$ at 23.5, 24.15, and 24.20 MeV(Lab). These energies are the same as those at which angular distributions were measured for the inelastic $\alpha$ scattering. From these elastic scattering angular distributions, a search for optical model parameters has been made by the code RAROMP\textsuperscript{2}. The resulting optical model sets are then used as starting values in the coupled channels code INCH\textsuperscript{3}. These calculations are presently underway.
References


III. REACTIONS AND LEVELS IN MEDIUM TO HEAVY NUCLEI

15. Search for Low $J^\pi = 0^+$ States in $^{48,50}$Cr, $^{52}$Fe and $^{102}$Pd by (p,t) Reactions

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The (p,t) and (t,p) reactions are very effective in detecting $J^\pi = 0^+$ states in nuclei because even very weak $L = 0$ transitions show a clear and characteristic diffraction pattern.

In the $1f_{7/2}$ shell, virtually all of the even-even, nonclosed shell nuclei have low excited $0^+$ states around 2-3 MeV, usually with known $2^+$ states at $\sim$700 keV higher, connected to them by enhanced E2 transitions. However, in the case of $^{48}$Cr there is conflicting evidence $^1,^2,^3$ for an $0^+$ state near 1.9 MeV, and in $^{50}$Cr and $^{52}$Fe no $0^+$ states have been found below $\sim$4 MeV. Since the Q-values for this region are $\sim$15 MeV, we are using the Strasbourg MP-tandem ($E_p \leq 26$ MeV) to search for these states. In addition it is planned to run $^{104}$Pd(p,t)$^{102}$Pd to search for low spin (down to $J^\pi = 0^+$) members of higher "side bands" seen in (HI,Xn) reactions. Lower members of these side bands are predicted by a recent interacting Boson model of Arima and Iachello $^4$.

References

Measurement of the $^{119}_{\text{Sn}}(p, n)^{119}_{\text{Sb}}$ Reaction to the Ground State

Isobaric Analog and Evidence for Excited Analogs

C. H. Poppe, S. M. Grimes* and C. Wong*

Recent measurements at this laboratory$^1$ of the $(p, n\tilde{p})$ reaction on $^{119}_{\text{Sn}}$ have shown that analogs of low-lying excited states of $^{119}_{\text{Sn}}$ are populated in the $(p, n)$ reaction. These measurements, which used coincidence between the neutrons and decay protons, demonstrated that some excited analog states decay to excited states of $^{118}_{\text{Sn}}$ producing protons of approximately the same energy as those produced in the ground-state to ground-state transition. Consequently, non-coincidence $(p, n\tilde{p})$ measurements would overestimate the width for proton decay of the analog state. This effect was originally suggested by Grimes et al.$^2$, to account for the fact that non-coincidence $(p, n\tilde{p})$ measurements on $^{208}_{\text{Pb}}$$^3,4$ and $^{209}_{\text{Bi}}$$^5$ yielded ground state analog cross sections greater than those obtained from the $(p, n)$ reaction using standard neutron time-of-flight spectrometry. The coincidence measurements, therefore, allow an accurate proton decay width to be extracted once the cross section for the formation of the analog state is measured. This was done by measuring the $^{119}_{\text{Sn}}(p, n)$ reaction using the neutron time-of-flight spectrometer at the Lawrence Livermore Laboratory cyclograaff.

Protons were accelerated to energies of 17, 18, 19 and 20 MeV by the cyclograaff -- an EN tandem Van de Graaff accelerator with a 15-MeV AVF cyclotron as injector. Neutron energy spectra at 16 angles between $3.5^\circ$ and $159^\circ$ were obtained simultaneously by measuring
the time of flight over the 10.8 m flight path between target and each of the 16 detectors. NE 213 scintillators were used as detectors and pulse-shape discrimination was used to reduce background from pulses produced by gamma rays. The target was a 4.62 mg/cm² metallic foil of 89.8% $^{119}$Sn.

Peaks in the time-of-flight spectra corresponding to excitation of the isobaric analog state are superimposed on a neutron continuum. In order to determine the counts in the peak a least-squares fitting routine was used which fits a Gaussian to the peak superimposed on a linear or linear plus quadratic background. Differential cross sections were calculated from the counts in the peaks using the previously determined detector efficiencies and the known target thickness.

Figure 16-1 shows the c.m. differential cross section for $^{119}$Sn($p,\alpha$)$^{119}$Sb(IAS) for 17, 18, 19 and 20 MeV bombarding energy. The errors indicated include statistical uncertainties as well as an estimated error for extracting the peak from the neutron continuum.

Integrated cross sections were extracted by fitting each angular distribution with a Legendre polynomial series. The results are presented in Table 16-1, where the error quoted was determined from both the relative errors in the angular distributions and the goodness of fit of the polynomial series to the data. The behavior of the integrated cross section as a function of bombarding energy is similar to that observed in experiments on other nuclei[^6][^7][^8]. The angular distributions presented here and the integrated cross sections are compared to the ($p,\alpha p$) measurements in Sec. 17 of this Report.
By using coincidence techniques, Fitzgerald, et al., measured the yield of neutrons to analogs of excited states over various intervals of excitation energy. At 19 MeV bombarding energy, over the range 0.9 to 1.5 MeV above the ground state analog, the yield was found to be about 0.18 of that for the ground state at forward angles. In order to see if this yield was consistent with the present experiment, the following procedure was used: For the 19 MeV, 24º neutron time-of-flight spectrum, a peak shape was determined from the ground state analog peak after subtraction of a smooth background. This experimentally determined shape was reduced by various factors and added to a smooth background at points in the time-of-flight spectrum corresponding to excitation energies of analogs of known excited states of the target nucleus. A particular example is shown in Fig. 16 -2. Here, the ground state analog peak shape has been reduced by factors of 0.1 and 0.08 and added to a smooth background at flight times corresponding to excitation energies 1.09 and 0.92 MeV respectively above the ground state analog. The solid curve in the figure is the result of this procedure and the dashed curve is the smooth background. Although the error bars on the data points are large there is evidence for excited analogs at these 2 energies. The reduction factors used here produce the same total excited analog state yield as measured by Fitzgerald et al., over the excitation energy interval 0.9 to 1.5 MeV above the ground state analog. In addition to the analogs of the 1.09 and 0.92 MeV states, analogs of states at 0.787 and 1.35 could also contribute in this interval of excitation energy, but the present data indicate that they are not as strongly excited.
References

*Lawrence Livermore Laboratory.


Table 16-1. Integrated cross sections (mb) for the $^{119}$Sn(p,n) reaction to the ground state analog as a function of bombarding energy (MeV).

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Fig. 16-1. Angular distribution for the $^{119}\text{Sn}(p,n)^{119}\text{Sb}$ reaction to the ground state analog at bombarding energies of 17, 18, 19 and 20 MeV.
Fig. 16-2. Portion of a neutron time-of-flight spectrum at $24^\circ$ and 19 MeV bombarding energy showing the ground-state analog peak and possible locations of excited analog states. Notice the suppressed zero for the ordinate.
Comparison of the Formation and Decay of the g.s. Analog Studies of $^{119}$Sn

D. H. Fitzgerald, J. S. Lilley, and C. H. Poppe

By detecting neutrons in coincidence with ($p$) protons from the decay of the analog state (IAS) we have successfully measured $^{119}$Sn(p,n) angular distributions\(^1\) on an unpulsed machine with a relative accuracy which in general is better than that using pulsed beams and long flight paths. The improved accuracy is possible because the coincidence technique greatly reduces the neutron continuum under the IAS peak which is the major source of uncertainty in (p,n) singles experiment.

In order to determine absolute cross-sections or partial proton decay widths of the analog states it was necessary to calibrate the coincidence method. This is being done first by measuring at Lawrence Livermore Laboratory (LLL) the $^{119}$Sn(p,n)$^{119}$Sb (IAS) reaction at several energies, using the same target and including with the already calibrated LLL detectors one of the complete detector assemblies used in the Minnesota coincidence experiment (see sections 16 and 37). In this way, the Minnesota data have been normalised and the partial decay width $\Gamma_p/\lambda$ has been determined for the decay of the analog of the ground state of $^{119}$Sn.

In addition, an experiment is underway (see section 18) to measure ($p$,n$\tilde{p}$) on two targets for which the corresponding analog states in the neighbouring isobars are neutron bound, and thus, since $\Gamma_p/\lambda \approx 1$, a further check can be made of the experimental efficiency.
Fig. 16-1 of section 16 shows the angular distributions taken at Livermore. They exhibit a transformation from a forward-peaked oscillatory function at 17 MeV to a distribution with a pronounced forward dip and a single pronounced forward maximum at the higher energies. Data taken by Carlson et al.\(^2\) at Colorado show that at 22.8 MeV the forward dip has filled in again.

The Colorado data were fitted satisfactorily in magnitude and shape with a DWBA calculation using either: (Set I) nucleon-nucleus potential parameters obtained by Becchetti and Greenlees\(^3\) (B-G) from an analysis of a large quantity of nuclear elastic-scattering data. (Set II) A set of parameters, (Colorado)\(^2\) derived from those of Becchetti and Greenlees, which are more nearly consistent with the Lane formalism and which were adjusted to give the best fit to the 23 MeV data. These two sets of parameters are listed in Table 17-1.

As an initial analysis, we have compared our data with predictions of these two parameter sets. The results at 19- and 17-MeV are shown in Fig. 17-1 and Fig. 17-2. The Livermore data are shown as solid circles; the Minnesota data (multiplied by a factor of about 3) are shown as open circles, and illustrate the quality of the relative data obtainable using the coincidence technique. The two sets of data track exceedingly well.

At 19-MeV, (Fig. 17-1) apart from the region of the forward angle dip, the calculated curve using the B-G parameters (Set I) gives a reasonable fit to the overall magnitude and shape of the
data. While the Colorado parameters (Set II) gave the best representation of the 22.8 MeV data, they do not give the better fit at 19 MeV. At 17 MeV, (Fig. 17-2) the disagreement between theory and experiment is considerably greater than at the higher energies. While the oscillations and general fall-off of the cross section with angle are reproduced, the minimum at large angles is filled in and the overall magnitude of either fit is about a factor of 2 too low. It should be pointed out that the Colorado parameters contain an ad hoc strength parameter, $S$ (see Table 17-1), adjusted to best reproduce the magnitude of the 22.8 MeV data.

Fig. 17-3 summarizes the results for the integrated $(p,n)$ cross section to the analog of the $^{119}$Sn ground state as a function of incident (lab) energy. The Minnesota $(p,np)$ data, shown as open circles, are scaled to fit the Livermore $(p,n)$ data (closed circles). The normalization factor yields a factor of 0.33 for the relative proton decay width of the g.s. analog.

The excitation function exhibits a broad maximum in the total yield near 17.5 MeV, which is about 3.7 MeV above threshold. Similar energy dependences have been noted by other groups for a wide range of nuclei. This feature is not reproduced by the B-G global prescription for the nucleon-nucleus interaction, and either a different energy dependent set of parameters must be used, or an additional energy dependent reaction mechanism must be included.

References


Parameters Used in DWBA Fits

**Neutron Optical Potential**

\[ U_0(r) = -V_0 f_R(r) - iW_0 f_I(r) + iW_a a_{I0} \frac{df_I(r)}{dr} + V_{SO} \frac{s_{SO}}{r} + \frac{df_{SO}(r)}{dr} \]

The radial shapes all have Saxon-Wood form.

**Isospin Potential**

\[ U_1(r) = \frac{2(N-Z)^{1/2}}{A} V_1 f_R(r) + iW_1 a_{I1} \frac{df_I(r)}{dr} \]

<table>
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<td>5.40 - 0.32E_n - 24.0 \frac{N-Z}{A}</td>
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<td>(0.22E_n - 1.56)**</td>
<td>(0.22E_n - 2.70)**</td>
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<td>\frac{1}{\pi} \left[\frac{3r_{I1}^2}{2} \right]^{1/2}</td>
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\( r_{RMS} = 1.72 \text{ fm} \)

For both Sets I and II: \( r_R = 1.17 \text{ fm}, a_R = 0.75 \text{ fm} \)

\( r_{SO} = 1.01 \text{ fm}, a_{SO} = 0.75 \text{ fm} \)

*For both Sets I and II, the proton optical parameters are those of Ref. 3.

**Or zero, whichever is greater.**
$^{119}\text{Sn}(P,n)^{119}\text{Sb}(\text{g.s. IAS}) \rightarrow \vec{p} + ^{118}\text{Sn}$

$E_p = 19.0$ MeV

- LIVERMORE
- MINNESOTA

$\sigma_{CM}(\theta_n)$, mb/sr

$\theta_n(\text{CM}), \text{DEG.}$
\[ ^{119}\text{Sn}(p,n)^{119}\text{Sb}(\text{g.s. IAS}) \rightarrow \vec{p}^+^{118}\text{Sn} \]

\( E_p = 17.0 \text{ MeV} \)

- LIVERMORE
- MINNESOTA

\[ \sigma_{\text{CM}}(\theta_n), \text{mb/sr} \]

\[ \theta_n(\text{CM}), \text{DEG.} \]
INTEGRATED CROSS SECTIONS
\[ {}^{119}\text{Sn}(p,n){}^{119}\text{Sb}(\text{g.s. IAS}) \]

\[ \frac{\Gamma_p}{\Gamma} = 0.33 \pm 0.02 \]

\[ \sigma_{\text{INT}}, \text{mb} \]

\[ E_p, \text{MeV} \]

- \( \sigma(p,n) \text{ LIVERMORE} \)
- \( \sigma(p,n) \times \frac{\Gamma}{\Gamma_p} \text{ MINNESOTA} \)
- \( \sigma(p,n) \text{ COLORADO} \)

FIG. 17-3
The $^{91}\text{Zr}(p, np)^{90}\text{Zr}$ and $^{95}\text{Mo}(p, np)^{94}\text{Mo}$ Reactions

D. H. Fitzgerald, J. S. Lilley, and C. H. Poppe

Data have been taken for the reaction: $^{95}\text{Mo}(p, np)^{94}\text{Mo}$ and $^{91}\text{Zr}(p, np)^{90}\text{Ar}$ using the neutron-proton coincidence technique which has been described elsewhere$^{1,2}$. In these particular cases, the isobaric analogs in $^{95}\text{Tc}$ and $^{91}\text{Nb}$ of the corresponding target ground states are neutron bound and proton unbound. Thus $\Gamma_{n}/\Gamma_{p}$ is essentially unity for these analogs, and since our neutron detectors have been calibrated (see section 37) we will be able to determine absolute $(p, n)$ differential cross sections.

$^{95}\text{Mo}$ was chosen because $(p, n)$ data have been taken by the Livermore group at a number of energies above 16 MeV$^{3}$, and therefore it serves as a direct check on the overall efficiency of our experiment. We hope also to extend the measurements of Ref. 3 below 16 MeV, closer to threshold, and further explore the broad resonance-like structure in the total $(p, n)$ yield which was seen for all the molybdenum isotopes. $^{91}\text{Zr}$ was chosen because it is close to the semi doubly-magic $^{90}\text{Zr}$. Its energy levels are reasonably well spaced, and the ground and several excited analog states are neutron bound. It should be one of the few cases for which we will be able to obtain definitive information on the proton decay branches of a number of the analog states.

The only changes to the basic neutron-proton coincidence technique described in previous reports$^{1}$ involved the proton detection system. The two E-VETO detector telescopes had 0.76 cm diam. apertures at 2.8 cm from the target and were oriented to detect
particles emitted at $\pm 135^\circ$ in the vertical plane. This arrange-
ment did not interfere at any angle in the horizontal plane with
the detection of neutrons by the array of five NE213 scintillators.
The proton timing signal was generated using a timing filter
amplifier and a constant fraction discriminator. This gives a
greater dynamic range than the (L.E.) time-pick-off system we used
previously.

The $^{91}\text{Zr}$ and $^{95}\text{Mo}$ targets were bombarded with approximately
30 $\mu$A of protons in the "eight-foot" chamber on the W15° beam line.
The beam spot was defined by a 2 mm collimator midway between the
two beam line quadrupole doublets, and essentially no beam (<.01 $\mu$A)
was intercepted by the carbon clean-up aperture at the scattering
chamber entrance. The beam was dumped 3 m from the target in a
shielded Faraday cup. Data were taken with neutrons detected over
the angular range 6° to 156° at 6° intervals.

The limited forward range of the sliding seal on the scattering
chamber made it necessary to take the data below 36° using an inter-
nal Faraday cup. The scintillators were moved further away from the
target, and, with careful shielding, the accidental background rate,
although considerably worse than at the larger angles, was accept-
able.

We have taken complete angular distributions on $^{95}\text{Mo}$ at 15 MeV
and on $^{91}\text{Zr}$ at 14 and 15 MeV. The uncorrected 15 MeV angular distri-
butions shown in Fig. 18-1, are similar to the 16 MeV Livermore
data on $^{95}\text{Mo}$.

Evidence for the population and decay of excited analog states
is seen in the proton-gated neutron spectra taken on $^{91}\text{Zr}$. The
evidence for this process in $^{95}$Mo(p, $\sim$p) is much weaker, as expected, since only the ground IAS in $^{95}$Tc is neutron bound. It is planned to study the proton decays of these higher analogs in considerably more detail. The raw coincidence data are stored on magnetic tape and the runs can be reanalysed with neutrons gated with any proton energy and vice-versa.

The measurements will be extended to 16 MeV as soon as new accelerator tubes are installed in the MP tandem this fall.

References


$^{91}\text{Zr}(p,n\bar{p})^{90}\text{Zr}$

$E_{INC} = 15.0$ MeV

$^{95}\text{Mo}(p,n\bar{p})^{94}\text{Zr}$

$E_{INC} = 15.0$ MeV
19. Search for Weak-Coupling Core Excited States in Odd-Z Heavy Nuclei

R. Seltz* and Harbans L. Sharma**

A great deal of information on even-even nuclei in the transition region between the rare earths and lead has been gathered in recent years. In order to get a better understanding of the structure of the neighbouring odd-Z nuclei we have measured angular distributions for the (p,t) reactions on the following targets: $^{181\text{Ta}}$, $^{197\text{Au}}$, $^{203\text{TI}}$, and $^{205\text{Tl}}$.

The Enge split-pole spectrograph with position sensitive detectors was used to achieve an energy resolution of 10-20 keV depending on the target at an incident energy of 19 MeV. Measurements were made between $10^\circ$ and $60^\circ$ with $5^\circ$ steps.

Preliminary results for some of the measured angular distributions are given in Fig. 19-1 - 19-3. For clarity the experimental points have been connected with solid lines.

Since the ground state of $^{181\text{Ta}}$ has $J^\pi = 7/2^+$, most of the transitions allow several values of $L$. Except for $L = 0$ it is not possible to deduce the transferred $L$ by comparison with standard two-nucleon transfer calculations.

All g.s. $\rightarrow$ g.s. transitions have typical $L = 0$ shapes, confirming therefore the spin of the final nuclei e.g. $J^\pi = 7/2^+$ for $^{179\text{Ta}}$.

Figs.19-1 and 19-3 show many other possible $L = 0$ transfers for excited states in $^{179\text{Ta}}$ and $^{195\text{Au}}$.

$^{181\text{Ta}}(p,t)^{179\text{Ta}}$

Several rotational bands have been proposed in $^{179\text{Ta}}$ from $\gamma$-ray studies\(^1\). The $7/2^+$ members of the $5/2^+[402]$ and $1/2^+[411]$ bands are not seen in our experiment although they could show $L = 0$ angular
distributions if there is bandmixing. The five levels $J^\pi = 7/2^+$ above 1527 keV we observe, do not fit in any of the models so far proposed for $^{179}$Ta. They will be analysed in the framework of the weak-coupling model on basis of the results of the $^{180}(p,t)^{178}$Hf reaction. Fig. 19-2 shows the angular distributions and their relative intensities for the members of the g.s. rotational band as proposed in ref. 1.

$^{197}\text{Au}(p,t)^{195}\text{Au}$

Goldman et al.\textsuperscript{3} have studied this reaction at 17 MeV and reported an L = 0 transfer for a level at 1.35 MeV. We confirm this result and hence $J^\pi = 3/2^+$ for this level. However we find a (p,t) cross section ratio to the g.s. of $\sim 2.5\%$, which is ten times smaller that given by the previous authors. Our value is in good agreement with the assumption of a weak-coupling collective state based on the 0\textsuperscript{+} of $^{194}$Pt at 1.55 MeV\textsuperscript{4}.

Two other L = 0 transfers for previously unknown states at 1110 keV and 1520 keV have been observed.

$^{205}\text{TI}(p,t)^{203}\text{TI}$ and $^{203}\text{TI}(p,t)^{201}\text{TI}$

The $^{205}\text{TI}(p,t)^{203}\text{TI}$ and $^{203}\text{TI}(p,t)$ no L = 0 transfer was seen for $E_x < 2.5$ MeV except for the ground state.

Many other angular distributions have been measured for the targets studied. Their analysis is in progress.

References


*Permanent address: C.R.N., Laboratoire des Basses Energies, Strasbourg, France

**Present address: Schuster Laboratory, Manchester, Great Britain
Fig. 19-1. Experimental angular distributions of $t$ from $L = 0$ transfers to states in $^{179}$Ta.

Fig. 19-2. Experimental angular distributions for the members of the g.s. rotational band from $^{181}$Ta($p,t$)$^{179}$Ta.

Fig. 19-3. Experimental angular distributions of $t$ from $L = 0$ transfers to states in $^{195}$Au.
20. **Analysis of Two-Particle Transfer Reactions on Deformed and Shape Transition Nuclei, 150 ≤ A ≤ 192**

N. Hintz, M. Sano, T. Takemasa, and M. Wakai

(University of Kyoto, Osaka University)

Extensive data exists\(^1\),\(^2\) on \((p,t)\) and some on \((t,p)\) reactions populating ground state rotational bands, collective \(\beta, \gamma\) and pairing excitations, and "shape isomeric" states in the region \(A = 150\) to \(192\). To date, only a few of the ground band\(^3\) and excited \(K = 0\) band\(^4\),\(^5\) intensities have been discussed theoretically. These calculations have used single particle levels calculated in deformed potentials, with no attempt being made to fit the observed one quasi-particle energies. Each calculation has used a different combination of pairing and quadrupole forces to obtain a rough, semi-quantitative, fit to the data on \(K = 0\) bands. It has not been clear from this work what was the cause of the large variation in strength to these bands in the rare earth region.

The purpose of this work, began while the author (N.H.) was on sabbatical leave at Kyoto University, is to explore systematically various force combinations and single particle level schemes to determine which factors are critical in reproducing the observed distribution of \(L = 0\) strength to excited \(K = 0\) bands. In addition, ground state \(L = 0\) strengths in even nuclei, and lowest \(L = 0\) transitions to "favored" bands (same Nilsson orbit as target) in odd-\(N\) nuclei are being analyzed. Separate calculations are being made, to test wave functions and reaction mechanisms, for two quasi-particle transitions (pickup of particles from different Nilsson orbits). Our tentative conclusion, to date, is that
relative ground state (or lowest \( L = 0 \) in odd-N nuclei) cross sections from \( A = 152 \) to 192 are fairly well reproduced (Fig. 20-1) by assuming pure monopole pairing forces and using the single particle level schemes of Ogle, et al.\(^6\), which have been determined by fitting the observed one quasi-particle states, together with a zero range DWBA two particle transfer program (TWOPAR). However, a pure monopole pairing force, while giving the correct strength to the excited \( K = \) \( ) \) bands from about \( 164\) \( ^{164}\)Er to \( 184\) \( ^{184}\)W (Fig. 20-2) fails to give a low enough energy for all of the nuclei and also fails to reproduce the relatively large Sm isotopes. Some additional quadrupole-pairing or ordinary quadrupole forces seem required to correct these deficiencies. Calculations are continuing to determine the necessary force strengths (M. Sano and M. Wakai). Data on \( L = 0 \) strength to "shape isomeric" states in the Sm isotopes is also being analyzed (N.H. and T.T.).

References

Lowest $L=0$ (p,t) Transitions

- $E-E$
- $\times$ odd-$N$
- $\Box$ odd-$Z$

$\circ$---$\circ$ Calculated
(X) Upper Limit

Fig. 20-1
The localization of El strength as exhibited in the electric dipole giant resonance is a well known phenomenon, which has been intensively studied, both theoretically and experimentally in nuclei throughout the periodic table. Interest in the giant resonance region has revived lately as more experimental techniques have been used to study this important phenomenon. The use of polarized proton beams in \((p,\gamma)\) studies and the inelastic scattering of hadrons and electrons have located EO, M1 and E2 strength in the giant resonance region. The discovery of these additional multipoles has stimulated extensive investigation, and a new picture of multipole strength in this region is presently emerging. Although investigations of these resonances by capture reactions provide a valuable aid for understanding their nature, the \(\alpha\) capture reaction in particular has been studied only in light or medium weight nuclei below \(A = 40\).

We have developed a technique for studying \(\alpha\)-capture by \(^{208}\text{Pb}\) and \(^{209}\text{Bi}\) in the vicinity of the giant resonances. Excitation functions have been measured for the reactions \(^{208}\text{Pb}(\alpha,\gamma)^{212}\text{Po}\) and \(^{209}\text{Bi}(\alpha,\gamma)^{213}\text{At}\). \(\alpha\) bombarding energies between 15 and 24 MeV, which corresponds to a range of excitation energy in the compound nuclei of about 8-17 MeV. The reaction yields exhibit a strong compact giant resonance, with central energy at the expected location of the giant dipole resonance.
A. Measurement of the cross-section

The half lives of $^{212}$Po and $^{213}$At are 300 and 110 nanoseconds, respectively so that the cross-sections could be determined by counting the residual $\alpha$-activity in situ, using a pulsed-beam technique. The procedure was as follows. For $^{208}$Pb($\alpha$,\gamma), the incident $\alpha$-particle beam was pulsed with an irradiation period of about 400 nanoseconds followed by a beam off target period of about 1000 nanoseconds. (For $^{209}$Bi($\alpha$,\gamma) ON/OFF times of 250 and 750 ns respectively were used. During a selected part of the beam off period, $\alpha$-activity was counted in a 100 mm$^2$ Si surface barrier counter located 3 cm from the target, and at 135$^\circ$ with respect to the incident beam direction.

Since the beam profile was not perfectly sharp (it took $\sim$60 nanoseconds to switch the beam) the residual activity was counted about 30-50 nanoseconds after the incident beam was deflected fully off the target. The counting duration was about 700 nanoseconds.

A time-to-amplitude converter was used to measure the interval between a fiducial point in the beam switching pulse and the $\alpha$-detector signal: this information, together with the corresponding $\alpha$-particle pulse-height was stored in a 2-parameter data array.

Fig. 21-la illustrates an $\alpha$-particle spectrum collected during the counting period for the $^{208}$Pb target. The incident $\alpha$-particle energy was 20 MeV. The $\alpha$-particle groups due to the decay of $^{212}$Po and $^{211}$Po produced in the $\alpha$,\gamma and $\alpha$,n reactions are clearly identified. In this spectrum, note the suppression of the elastic $\alpha$-particle group, and the high quality of this spectrum with respect to background noise. The suppression of background noise was partly due to pile-up
rejection circuitry. The $\alpha$-detector count rate is quite high (16 x $10^3$ counts/sec) during irradiation, as compared to the count rate during the counting period (as low as 5 counts/hr); a not unlikely event is the detection of an $\alpha$-particle pulse during the counting period with its corresponding pulse shape distorted by a previously occurring pulse corresponding to an elastic scattering event. These distorted pulses tend to fill in the pulse-height distribution during the counting interval, and due to the great difference in rates, become a serious experimental difficulty. Simple pulse shape analysis was used to reject these events. The presence in the spectrum of the $\alpha$-particles at 7.45 MeV due to the decay of $^{211}$Po ($t_{1/2} = 25$ seconds) was not a serious drawback since their energy is less than the $\alpha$-particles from the decay of $^{212}$Po. They were used in energy calibration, and, since the $\alpha$-n reaction cross section is known, as a monitor of the $\alpha$-y reaction yield as well. Since two-parameter data was collected it was possible to employ digital pulse-height selection and examine the time distribution of the $\alpha$-particle group with energy 8.78 MeV. We attribute this group to the decay of $^{212}$Po not only on the basis of its energy, but also on the basis of its time distribution. In Fig. 21-1c the solid line drawn through the data points corresponds to a half-life of 300 nanoseconds. Similar spectra are shown in Fig.21-1b and 21-1c for the $^{209}$Bi + $\alpha$ reaction. In Fig. 21-b we have labeled the group due to the decay of $^{213}$At; its decay is illustrated in Fig. 21-1c.
B. Results

The yield of $\alpha$-particles from the $\alpha$-$\gamma$ reaction was extracted from these data by integrating the area under the appropriate peak; a straight line background was used. At the higher bombarding energies the $^{208}\text{Pb}(\alpha,n)^{211m}\text{Po}$ becomes important as it decays with a $7\%$ branch to $^{207}\text{Pb}$, $E_\alpha = 8.88$ MeV. However, the cross-section has been measured by Barnett and Lilley and thus the correction is easily made. Since a reliable correction depends only on the ratio of $^{211}\text{Po}/^{211m}\text{Po}$, the error introduced by this correction is negligible.

Fig. 21-2 illustrates the excitation function of the $^{208}\text{Pb}(\alpha,\gamma)^{212}\text{Po}$ reaction measured in this way. The ordinate is an absolute cross-section, with an estimated systematic error $= 5\%$. The excitation function shows a pronounced maximum at $E_\alpha \approx 22$ MeV, with a full-width-half-maximum $\approx 3.75$ MeV. The open circles illustrate the measured excitation function for $^{213}\text{At}$; clearly the resonance structure is in both $^{212}\text{Po}$ and $^{213}\text{At}$. The arrows labeled E1 and E2 indicate the expected central location of the giant E1 and E2 (isoscalar) resonances computed from $E_\chi = 77A^{-1/3}$ and $63A^{-1/3}$, respectively. The observed resonance central energy is in agreement with the expected location of the known giant dipole resonance. The known E0 strength is at $E_\chi = 8.9$ MeV in $^{208}\text{Pb}$; the known E2 strength is at $E_\chi = 10.1, 10.6$, and $11.4$ MeV; the giant dipole resonance as measured in $(\gamma,n)$ work is located at $13.4$ MeV, with a width $\Gamma = 4$ MeV. Based on the location, width, and magnitude of the cross-section, it seems that this reaction is principally exploring E1 strength. Detailed analyses
together with more extensive data acquisition, particularly at higher incident bombarding energies, are underway.

References


Fig. 21-1. Time and energy spectra of the residual activity formed in the (α,γ) and (α,n) reactions on 208Pb and 209Bi.

(a) 208Pb + α 20 MeV

(b) 209Bi + α 21 MeV

(c) 300 ns

110 ns

212Po

213At

Relative Activity

Time (ns)
The $^208\text{Pb}(\alpha)n$ threshold energy is marked by the arrow near $15.26$ MeV. The scale at the top of the figure shows the excitation energy in $^{212}\text{Pb}$ corresponding to the $\alpha$ particle energy labeled on the abscissa. The scale at the top of the figure shows $^{208}\text{Pb} + \alpha$ and $^{209}\text{Bi} + \alpha$. The scale at the top of the figure shows the excitation energy at the giant resonance region for $^{208}\text{Pb}$. (a, n) reaction. The scale at the top of the figure shows the excitation energy at the giant resonance region for $^{212}\text{Pb}$. (a, n) reaction.
In this report we present measurements of the $^{208}\text{Pb}(\alpha,\gamma)^{212}\text{Po}$ cross section which enable us to extend previous determinations\(^1\) of the total $\alpha$-particle reaction cross section $\sigma_R$ to energies below the $^{208}\text{Pb}(\alpha,n)$ threshold at $E_{\text{lab}}=15.26$ MeV. The data are consistent with upper limits we had obtained previously\(^2\).

The experimental technique, which is described in more detail in Section 21, used a pulsed beam of $\alpha$-particles (see section 40); the decay $\alpha$-particles from $^{212}\text{Po}$ were detected during the beam-off-target period; these $\alpha$-particles were identified by both their characteristic energy and their half-life. Data were taken in 1 MeV steps between 16- and 23 MeV, at 23.5 MeV, and in finer steps near the $(\alpha,n)$ threshold. Both $(\alpha,\gamma)$ and $(\alpha,n)$ data were recorded simultaneously. When normalized in the energy region 20-22 MeV, the $(\alpha,n)$ cross section data agree (within experimental error) with those of Ref. 1 over the entire energy range studied.

The results for the $\sigma(\alpha,\gamma)$ and $\sigma(\alpha,n)$ are tabulated in Table 22-1. In determining the $(\alpha,n)$ cross sections, the $\alpha$-decays of both the ground state and 1.45 MeV metastable state of $^{211}\text{Po}$ were recorded.

The $(\alpha,\gamma)$ data are also displayed in Fig. 21-2 on page 128. There is a distinct cusp in the $(\alpha,\gamma)$ cross section at the $(\alpha,n)$ threshold energy ($E_{\text{lab}}=15.26$ MeV). Below this threshold, the $(\alpha,\gamma)$ process represents virtually all the total reaction cross section and is seen to follow smoothly the steeply-rising $\sigma_R$ curve, which, above
threshold, is primarily \( \sigma(\alpha,n) \). Even at energies just above 15.26 MeV, neutron emission dominates the decay of the compound nucleus and the \((\alpha,y)\) cross section drops sharply.

Near 16 MeV there was evidence of fluctuations in both \( \sigma(\alpha,n) \) and \( \sigma(\alpha,y) \). The data, shown in Fig. 22-1, are not conclusive, however, and, since each data point required several hours of accelerator time, the phenomenon was not studied in any detail at this time. The fluctuations suggest that the compound-nucleus level-spacing at an excitation energy near 7 MeV is not small compared with the average level width, or even with the target thickness, which was about 30 keV. This is not inconsistent with estimates based on level density formulas, and measurements of level spacings in this region of the periodic table.

As reported previously, the motivation for this work was to explain the observations of Ref. 1 whereby optical model potentials which give good fits to accurate elastic scattering and reaction data at 77 MeV (just above the Coulomb barrier), predict, at lower energies, reaction cross sections which are systematically too high. The \((\alpha,y)\) cross sections we have determined are much too small to account for this discrepancy, which at 17 MeV ranges from 50\% to 150\% of the experimental value for different optical parameter sets. Furthermore, the good agreement of our relative \((\alpha,n)\) cross sections with the previous data lead us to conclude that the experimental information is complete and that the resolution of the problem lies in a detailed consideration of the energy dependence of the optical potential.
Since we do not expect the real part of the $\alpha^{208}\text{Pb}$ interaction to be sharply energy dependent at low velocities, the reaction data were fitted with optical model potentials which, while maintaining sufficient absorption in the nuclear interior, allow the surface imaginary term $W_{\text{surf}}$ to decrease gradually to zero as the incident $\alpha$-particle energy is reduced below the Coulomb barrier. The potential sets used were taken from those listed in Ref. 1 which gave "equivalent best" fits to the 22 MeV data.

The accuracy of these calculations, with $W_{\text{surf}} \approx 0$, was checked at very low incident alpha energies with the predictions of a WKB calculation of simple barrier penetrability. Agreement was within 10% at $E_\alpha = 15$ MeV and 5% at $E_\alpha = 10$ MeV. Thus the optical model calculations should be reliable over the entire energy range of the present work.

While all parameter sets fit the 22 MeV data, only those for which the real diffuseness parameter is greater than about 0.62 F fit the data between 16 and 18 MeV (see Fig. 22-2). Below 16 MeV, none of the potentials gives an adequate fit to the data, which suggests that either the absorption in the nuclear interior is very low or that compound elastic scattering is significant. The latter explanation is not expected to be the case above the neutron threshold because of the low $\alpha$-penetrability compared with that of the neutron. Moreover, the evidence for fluctuations in $\sigma_R$ suggest that, below 16 MeV, the data are beginning to reflect the properties of individual levels. The nuclear transparency will show corresponding rapid energy fluctuations and, hence, the observed reaction cross section
may lie well below that of a calculation based essentially on con-
tinuum theory.

In conclusion, we note that fits to the data between 22- and
17-MeV select an interaction potential with a real diffuseness of
about .65 F and a surface absorption which is generally small but
is quite significant for $E_\alpha = 22$ MeV and above. An experiment
which bears on this point is being carried out; we are attempting
to determine the effect of the surface opacity on the interference
between Coulomb and nuclear excitation amplitudes.

References

2. J. S. Lilley and M. A. Franey, John H. Williams Laboratory of
3. J. R. Huizenga, A. N. Behkami, J. S. Sventeck, and R. W. Atcher,
<table>
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</table>

*Percentage relative errors are given in parentheses*
Fig. 22-1. $^{208}\text{Pb}(\alpha,n)$ and $^{208}\text{Pb}(\alpha,\gamma)$ cross sections near 16 MeV.

Fig. 22-2. Ratio of calculated to experimental total $^{208}\text{Pb} + \alpha$ cross sections.
IV. WORK WITH HEAVY IONS

23. Sub-Coulomb Neutron Transfer Calculations

M. A. Franey and J. S. Lilley

In the past few years, there have emerged several high speed computer codes\textsuperscript{1,2,3} which treat the six-dimensional integral of the DWBA matrix element exactly, and enable effects such as "finite-range"\textsuperscript{4} (size of the projectile) and "recoil"\textsuperscript{4} (center of mass shift due to mass transfer) and the effects of different interaction potentials on heavy ion transfer calculations to be treated exactly\textsuperscript{5}. These effects are demonstrably significant and their proper treatment has essentially brought the DWBA to calculational completeness.

However, there remain the well-known problems of optical potential ambiguities which limit much of the spectroscopic information obtainable. Consequently, we are expanding a program begun last year\textsuperscript{7} of exploring the sub-Coulomb, single neutron transfer reaction as a means of eliminating these distorted wave and interaction potential\textsuperscript{6} uncertainties. Here we report computations done with the exact, finite-range code LOLA\textsuperscript{1}.

Following the notation of ref. 5, we consider the stripping reaction $A(a,b)B$ (with $a = b + x$ and $B = A + x$) whose coordinates are described by Fig. 23-1. The DWBA matrix element is

$$T = \int d^3r_a d^3r_b \chi^*(r_b) \langle \Psi_B(r_{xA}) | \Delta V | \Psi_a(r_{bx}) \rangle \chi_a^+(r_a)$$

where $\chi$ are the distorted waves and $\Psi$ are the bound state wave functions. The interaction potential $\Delta V$ is separated into a nuclear and Coulomb part which take the following forms in the post representation:

$$\Delta V^N = v_{bx}^N(r_{bx}) + v_{bA}^N(r_{bA}) - U_{bB}^{OPTN}(r_b)$$

$$\Delta V^C = v_{bx}^C(r_{bx}) + v_{bA}^C(r_{bA}) - U_{bB}^{OPTC}(r_b)$$
Fig. 23-1. Coordinates of the DWBA transfer calculation.

N and C denote nuclear and Coulomb; U is the optical potential, \( V_{b\chi} \) is the bound state potential and \( V_{bA} \) is the core-core potential. Sub-Coulomb neutron transfers require only

\[
\Delta V = V_{b\chi}(r_{b\chi}) + V_{bA}(r_{bA}) - U_{OPTC}(r_b)
\]

since \( \Delta V_N = V_{b\chi} = 0 \).

Initially, LOLA had a few programming errors which seriously affected the calculations with \( \Delta V_C \) in the interaction potential. Corrections have been made and now agreement between pickup and stripping is satisfactory.

Calculational convergence can be relatively slow with LOLA and the step length DR and the upper limit of the radial integrations RMAX must be chosen with care. Estimates of DR based on a fraction of the projectile wave length, which may be sufficient for approximate treatments\(^8,9,10\) were generally too large for our sub-Coulomb calculations. Moreover, the integration region is not so well localized as in no-recoil calculations and a larger RMAX is often
required. Including the long-range Coulomb potential does not require an unusually large $R_{\text{MAX}}$, although a smaller step size in the angular integration (determined by the input parameter $\text{NGAUSS}$) was sometimes found necessary.

The computation time depends on the degree of convergence desired. 5% precision may be obtained in a relatively short run, however to improve this to 2% may take twice as long.

A significant saving in processing time has been made by using a least-squares fitting procedure to extrapolate the partial wave amplitudes beyond a limited value of $\ell$. The real-plus-imaginary parts of the LOLA transition amplitudes are converted to a modulus and phase angle which are fitted separately with analytic functions in a region near the $\ell$ value at which the amplitudes peak. Higher partial-wave amplitudes are then calculated with the functions determined in this way.

The moduli are fitted with a function $e^{a+b\ell+c\ell^2}$ to six LOLA amplitudes near $\ell_{\text{peak}}$. The corresponding phase angle differences are fitted to a quadratic and the extended partial wave phases are obtained by boot-strapping these differences onto the highest LOLA partial wave. This technique has worked surprisingly well and can result in a two to three fold reduction in computer time. The advantages of this method for sub-Coulomb transfers with $\Delta V^c$ are greater than at higher energies since the partial wave amplitudes tail off more slowly and $\ell = 0 - 60$ may be required for convergence. The sub-Coulomb phase angles could be calculated exactly. We have not done this since the fitting procedure works
well, and it would be needed for extrapolating at higher energies where the nuclear optical potential is important. In general, RMAX must be large if A_max is large, and in some cases the extrapolated partial waves were more accurate than those calculated by LOLA with an insufficiently large RMAX. Thus the savings in computer time may be greater than the roughly linear gain due to coupling fewer LOLA partial waves.

The sub-Coulomb DWBA cross section is highly sensitive to the size of the tail of each bound-state wave function and if good spectroscopic information is available (as is the case in the lead region) accurate information on, for example, the r.m.s. radius of the bound-state functions, may be obtained.

As an example, consider the reaction $^{208}\text{Pb}(^{12}\text{C},^{13}\text{C})^{207}\text{Pb}(\text{gs})$ at $E_{\text{LAB}} = 54$ MeV. In this case, the Coulomb terms increase the cross section by only 5.5%. The data (Fig. 23-2) show the characteristic smooth rise of a sub-Coulomb reaction at backward angles. The solid lines indicate the effect of varying the rms radius of the $3P_{1/2}$ neutron in $^{208}\text{Pb}$. A 6% increase in the rms radius produces an 60% increase in the cross section near $140^\circ$. Thus there is strong sensitivity and improved data should help pin down the bound state size. Also shown is a calculation done with the approximate recoil code of Buttle and Goldfarb which is roughly 20 times faster than LOLA and accurate to about 5% for reactions below the barrier. Thus extensive searching on the bound states can be done with this code using LOLA to scale the calculations.

The rms radii in Fig. 23-2 do not reflect the true values since they depend on the $^{13}\text{C}$ wave function which was fixed and on $S_{13\text{C}}$.
which was set equal to 1. A value of 0.61 has been quoted for $S_{13C}^{12}$. Further, a 4\% increase in the $^{13}C$ rms radius results in a 25\% increase in the cross section.

We are in the process, therefore, of collecting accurate data on the $^{208}\text{Pb}(^{12}C, ^{13}C)^{207}\text{Pb}$, $^{208}\text{Pb}(^{16}O, ^{17}O)^{207}\text{Pb}$ and $^{13}C(^{16}O, ^{17}O)^{12}C$ reactions below the barrier in an effort to determine the sizes of shell model orbitals and to calibrate the $^{12}C$ and $^{16}O$ projectiles for use in other reactions.

References
Fig. 23-2. Calculation of \( 208 \text{Pb}(12\text{C},13\text{C})207\text{Pb}(g.s.) \) at \( E_{\text{lab}} = 54 \text{ MeV} \).

- EXPERIMENT
- LOLA 3\( P_1/2 \) rms radius = 6.04
- LOLA 3\( P \) rms radius = 6.40
- BUTTLE & GOLDFARB
  rms radius = 6.04

\[ \frac{d\sigma}{d\Omega} (\mu b/sr) \]

\( \theta \) (deg)
In heavy ion induced single particle stripping reactions, the transitions with \( j_2 = \ell_2 + \frac{1}{2} \) are strongly enhanced\(^1\),\(^2\) over the ones with \( j_2 = \ell_2 - \frac{1}{2} \), where \( \ell_2 \) and \( j_2 \) are the orbital and total angular momenta of the transferred particle in the residual nucleus. Particularly simple is the proton transfer induced by the \((^{16}\text{O},^{15}\text{N})\) reaction since \( \ell_1 = 1 \) and \( j_1 = \frac{1}{2} \) for the orbital and total angular momenta of the particle transferred from the projectile. Specifically, in the \( ^{29}\text{Si}(^{16}\text{O},^{15}\text{N}(\text{g.s.}))^{30}\text{P} \) reaction, the transition to the \( 2^+ \) state at 1.454 MeV is of interest because shell model calculations predict\(^3\) a small \( 1d_{5/2} \) component for the transition to this state in addition to a strong \( 1d_{3/2} \) component. An objective of this study is to measure the small \( 1d_{5/2} \) component in this heavy ion induced transfer reaction and to compare the result with the shell model prediction.

As discussed in last year's annual report\(^4\), the \((^{16}\text{O},^{15}\text{N}(\text{g.s.}))\) reaction also needed to be done on a neighboring even-even nucleus, i.e., \(^{30}\text{Si} \). This reaction proceeds by a unique \( j \) transfer and thus allows a check on the reliability of the DWBA for the heavy ion induced reaction by comparison to previous \((^3\text{He},d)\) results. A summary of the allowed angular momentum transfers for transitions to the shell model orbits of interest is given in Table 24-1 along with the respective Q values, excitation energies, and \( J_f \) values of the final states in
the residual nucleus\(^5\). Here, \(\Delta L\) is the total angular momentum transfer which is restricted by \(|\ell_1 - \ell_2| \leq \Delta L \leq \ell_1 + \ell_2\) and \(|j_1 - j_2| \leq \Delta L \leq j_1 + j_2\).

As mentioned previously\(^4\), the strongly oscillatory angular distributions for the \(2s_{1/2}\) and \(1d_{3/2}\) transitions in \(30^P\) (as well as in \(31^P\)) are found to be out of phase. Calculations discussed in last year's report using the code RDRC, which does not include recoil, were found to fit the pure \(2s_{1/2}\), \(\Delta L = 1\) angular distributions reasonably well but failed to fit the \(1d_{3/2}\), \(\Delta L = 1\), (2) angular distributions. Since then, in an effort to determine the effects of recoil contributions, additional calculations have been made using the codes BRUNHILD\(^6\) which approximately includes recoil and LOLA\(^7\) which exactly includes recoil. The calculations using BRUNHILD, although using less computer time than those using LOLA, agree quite well with LOLA but only when matching conditions are good. Consequently, only the LOLA calculations are shown together with the data in Figs. 24-1 and 24-2. As can be seen, the phase of the structure of the \(1d_{3/2}\) transfer angular distributions still could not be fit even with the recoil contribution included. The calculated cross section for the \(\Delta L = 2\) recoil contribution to the states involving \(1d_{3/2}\) transfer was found to be an order of magnitude smaller than that for the \(\Delta L = 1\) contribution, both calculations being out of phase with each other. In fact, the shape of the \(\Delta L = 2\) recoil calculation by itself was found to give an almost perfect fit to the \(30^P(2^+)\) state involving \(1d_{3/2}\) transfer.
The effect of optical model parameters on the relative shapes as well as absolute magnitude of the calculations was also investigated. Two sets of optical model parameters listed in Table 24-2 were used in the fits of Fig.24-1. Set 1 (solid curves in Fig.24-1) was obtained by fitting the $^{16}_0 + ^{32}S$ data of ref. 8, while set 2 (dashed curves in Fig. 24-1) was used previously for DWBA calculations for the $^{16}_0, ^{15}N$ reaction. The calculations using these two sets did not give very different shapes for the angular distribution but differ by a factor of two in their absolute cross section. We were unable to find a modified parameter set which would fit the shape of the $ld_{3/2}$ state angular distribution.

Products of spectroscopic factors, $C_{1S_1}^2 * C_{2S_2}^2$, were extracted from the fits shown in Figs. 24-1 and 24-2 to the average cross sections. The results for $C_{2S_2}^2$ for proton stripping to P states are given in Tables 24-3 and 24-4 along with those values derived from other work and are in reasonable agreement with $(^3He,d)$. A $C_{1S_1}^2 = 1.75$ for proton pick-up from $^{16}_0$ was used. The mixed j transition to the $2^+$ state in $^{30}P$ at 1.454 MeV was found to proceed almost exclusively by $j = 3/2$ transfer as predicted by shell model calculations. However, a small $1d_{5/2}$ transfer strength has a strong effect on the cross section because of the aforementioned large enhancement of the $(l_2 + \frac{1}{2})$ transition over the $(l_2 - \frac{1}{2})$ transition and is very important at forward angles.

In conclusion, the failure to fit the shape of the angular distributions for both the $2^+$ state of $^{30}P$ at 1.454 MeV and the $3/2^+$ state of $^{31}P$ at 1.266 MeV has not, at present, been explained.
This failure and the dependence of absolute spectroscopic factors on different optical model sets require appropriate qualification of the reliability of the extracted $C_{2S}^2$ values. Acknowledging this qualification, in certain cases one might use the $(^{16}O, ^{15}N$ (g.s.)) reaction as a useful tool to untangle states of mixed j transition.

This work has now been completed and has been submitted for publication.

References
* Nuclear Structure Laboratory, University of Rochester.
3. B. H. Wildenthal, private communication (also quoted in ref. 20).
Table 24-1. Basic data\textsuperscript{a} of the reactions studied.

<table>
<thead>
<tr>
<th>Reaction\textsuperscript{b}</th>
<th>Q (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$</th>
<th>$n_2\ell_2j_2$\textsuperscript{c}</th>
<th>$\Delta L$\textsuperscript{d}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{30}\text{Si}$($^{16}\text{O}, ^{15}\text{N})^{31}\text{P}$</td>
<td>-4.830</td>
<td>0.0</td>
<td>$1/2^+$</td>
<td>2s 1/2</td>
<td>$1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.266</td>
<td>3/2$^+$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.334</td>
<td>5/2$^+$</td>
</tr>
<tr>
<td>$^{29}\text{Si}$($^{16}\text{O}, ^{15}\text{N})^{30}\text{P}$</td>
<td>-6.528</td>
<td>0.0</td>
<td>$1^+$</td>
<td>2s 1/2</td>
<td>$1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1d 3/2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.454</td>
<td>2$^+$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1d 5/2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.973</td>
<td>3$^+$</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Ref. 5.

\textsuperscript{b} Only $^{15}\text{N}(\text{g.s.})$ with ($n_1\ell_1j_1$) =(1p 1/2) was observed.

\textsuperscript{c} ($n_2\ell_2j_2$) of orbitals which contribute only weakly are in parantheses.

\textsuperscript{d} Normal $\Delta L$ are underlined.
Table 24-2. Optical Model Parameters used for both entrance and exit channels.

<table>
<thead>
<tr>
<th>Set</th>
<th>V  (MeV)</th>
<th>$r_r^{a)}$ (fm)</th>
<th>$a_r$ (fm)</th>
<th>W$_V$ (MeV)</th>
<th>$r_i^{a)}$ (fm)</th>
<th>$a_i$ (fm)</th>
<th>$r_c^{a)}$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.6</td>
<td>1.35</td>
<td>0.467</td>
<td>12.6</td>
<td>1.27</td>
<td>0.255</td>
<td>1.35</td>
</tr>
<tr>
<td>2$^b)$</td>
<td>100.0</td>
<td>1.14</td>
<td>0.68</td>
<td>20.0</td>
<td>1.20</td>
<td>0.60</td>
<td>1.35</td>
</tr>
</tbody>
</table>

$^a)$ Potential radii $R = r(A_1^{1/3} + A_2^{1/3})$

$^b)$ Ref. 9.
Table 24-3. Spectroscopic factors $C_{2S_2}^2$ for proton transfer to $^{31}$P states.

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$</th>
<th>$C_{2S_2}^2$ from $(^3\text{He},d)$</th>
<th>$C_{2S_2}^2$ from $(^{16}\text{O},^{15}\text{N})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>12MeV$^a$</td>
<td>15MeV$^b$</td>
</tr>
<tr>
<td>0.0</td>
<td>1/2$^+$</td>
<td>0.47</td>
<td>0.44</td>
</tr>
<tr>
<td>1.27</td>
<td>3/2$^+$</td>
<td>0.46</td>
<td>0.80</td>
</tr>
<tr>
<td>2.23</td>
<td>5/2$^+$</td>
<td>0.05</td>
<td>0.08</td>
</tr>
</tbody>
</table>

- $a^)$ Ref. 10.
- $b^)$ Ref. 11.
- $c^)$ Ref. 12.
- $d^)$ Ref. 13.
- $e^)$ Ref. 14 — without recoil.
- $f^)$ Ref. 15 — data of Ref. 14, analyzed with recoil. In Ref. 15 absolute $C_{2S_2}^2$ were multiplied by a factor of 2 to correct a possible error in the absolute cross sections of Ref. 14.
- $g^)$ Ref. 16 — without recoil. Here absolute $C_{2S_2}^2$ for g.s. transition is normalized to 0.5.
- $h^)$ Ref. 9 — An "$S_1" = 3.5$ was used in ref. 9 instead of the appropriate $C_{1S_1}^2 = 1.75$, i.e. values in this column should be multiplied by 2.
- $i^)$ this experiment.
- $k^)$ Ref. 17.
Table 24-4. Spectroscopic factors $c_{2s_2}^2$ for proton transfer to $^{30}_p$ states.

<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$J^\pi$</th>
<th>$j_2^\pi$</th>
<th>$(^3\text{He},d)$</th>
<th>$(^3\text{He},d)$</th>
<th>(d,n)</th>
<th>$^{16}_0,^{15}_N$</th>
<th>shell</th>
<th>model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>15MeV\text{a)}</td>
<td>25MeV\text{b)}</td>
<td>8MeV\text{c)}</td>
<td>60MeV\text{d)}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>$1^+$</td>
<td>$1/2^+$</td>
<td>0.48</td>
<td>0.49</td>
<td>0.47</td>
<td>0.51</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>1.454</td>
<td>$2^+$</td>
<td>$3/2^+$</td>
<td>0.33</td>
<td>0.32\text{f)}</td>
<td>0.34</td>
<td>0.54</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5/2^+$</td>
<td>(0.24)\text{f)}</td>
<td></td>
<td></td>
<td>0.05</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>1.973</td>
<td>$3^+$</td>
<td>$5/2^+$</td>
<td>0.22</td>
<td>0.034</td>
<td>0.06</td>
<td>0.10</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

\text{a)} Ref. 18.
\text{b)} Ref. 19.
\text{c)} Ref. 20.
\text{d)} this experiment.
\text{e)} Ref. 3.
\text{f)} if transition were purely 1d $3/2$ or 1d $5/2$, respectively.
$^{30}\text{Si}(^{16}\text{O},^{15}\text{N})^{31}\text{P}$

$E_{^{16}\text{O}} = 60.0 \text{ MeV}$

$E_x = 0.0 \text{ MeV}$
$J^\pi = 1/2^+$

$E_x = 1.266 \text{ MeV}$
$J^\pi = 3/2^+$

$E_x = 2.234 \text{ MeV}$
$J^\pi = 5/2^+$

Fig. 24-1
$^{29}\text{Si}(^{16}\text{O},^{15}\text{N})^{30}\text{P}$

$E_{^{16}\text{O}} = 60.0 \text{ MeV}$

$E_x = 0.0 \text{ MeV}$
$J^\pi = 1^+$

$E_x = 1.454 \text{ MeV}$
$J^\pi = 2^+$

$E_x = 1.973 \text{ MeV}$
$J^\pi = 3^+$

$\frac{d\sigma}{d\Omega_{\text{c.m.}}} (\text{mb/sr})$

$\theta_{\text{c.m.}}$

Fig. 24-2
Initially, elastic scattering of $^{16}\text{O}$ on two Si isotopes was measured in order to provide optical model parameters for the ($^{16}\text{O},^{15}\text{N}$) reaction described in Sec. 24. It was subsequently expanded further to test the ability of the optical model to reproduce the fine details of more accurately measured angular distributions.

Both angular distributions are shown on Fig. 25-1. They cover the laboratory angular range from $8.5^\circ$ to $50^\circ$ in steps of $0.5^\circ$. Data up to $35^\circ$ were taken by the Enge split-pole spectrograph, employing 4 position-sensitive detectors to collect four charge states of $^{16}\text{O}$ ($5^+, 6^+, 7^+, \text{and } 8^+$), and from $30^\circ$ to $50^\circ$ by means of an array of 6 surface-barrier detectors located in the scattering chamber. In all cases the angular acceptance of the spectrograph and each of the 6 detectors was $0.5^\circ$. An additional stationary detector at $-30^\circ$ was used as a monitor. Targets were self-supporting SiO foils enriched to more than 93\% and evaporated from a Ta crucible. The elastic scattering of $^{16}\text{O}$ on the Ta contamination, being pure Rutherford scattering at 60.0 MeV, served as a check on the overall efficiency of the system. When the spectrograph was used, that background was negligible. With the detector array the background made the largest contribution to experimental error varying from $\sim 1\%$ at $30^\circ$ to $\sim 30\%$ at $50^\circ$.

Fig. 25-1 shows that both distributions have diffraction-type patterns with well defined phases and amplitudes especially pronounced
Elastic Scattering of $^{16}O$ at 60.0 MeV
at large angles. Preliminary fits were obtained by searching with
the optical model program RAROMP\(^\text{1}\) starting with the two potential
sets, no. 1 (ref. 2) and no. 2 (ref. 3), listed in Sec. 24-2, p. 147.
Predictions based on both sets approximate the phase of oscillations
in the whole range of angles but fail to reproduce the amplitude'
especially beyond 50° in CM. In addition, fits obtained from set
no. 2 were better in this region but still not satisfactory. Work
on this matter is in progress.

References
1. G. J. Pyle, University of Minnesota, Report No. 1265-64, (1968),
   (unpublished).
2. R. M. DeVries, private communication.

26. Small Angle Structure in Inelastic $^{16}$O Scattering from $^{30}$Si
    H. P. Morsch, J. L. Artz, and D. Dehnhard

Heavy ion induced transfer reactions at energies sufficiently
above the Coulomb barrier are known to show strongly oscillating
angular distributions which can be interpreted by a simple diffrac-
tion model. Such oscillations are also expected in inelastic
scattering. However, the diffraction structure is expected to be
affected strongly at forward angles by the Coulomb-nuclear inter-
ference effect. Experimentally, the study of small angle inelastic
scattering is quite difficult because the peak from the inelastic scattering
is superimposed on the low energy tail of the elastic scattering peak.
This tail can be reduced considerably by use of clean apertures and
targets and a careful focusing of the beam. In this experiment we
studied scattering of 60 MeV $^{16}$O ions from $^{30}$Si using position
sensitive detectors placed along the focal plane of the split-pole
spectrograph. The differential cross sections for the inelastic
scattering to the $2^+$ state at 2.24 MeV are shown in Fig. 26-1 together with
the elastic scattering data (see section 25 of this report). At a
number of angles between $15^\circ$(c.m.) and $26^\circ$(c.m.) the cross sections
for inelastic scattering could not be measured because of $^{12}$C and
$^{16}$O contaminants in the target.

As expected a deep minimum is observed at $22^\circ$(c.m.) as a result
of Coulomb-nuclear interference. Surprisingly, another deep minimum
is seen at $11^\circ$(c.m.). To analyze these data, a DWBA calculation was
carried out using microscopic form factors (see section 31 of this
report). For the $2^+$ state of $^{30}$Si a simple ($s_{1/2}^{-1}d_3/2^{1}$) structure
was used which requires an effective charge $e_n = 2.2$ to fit the
experimental B(E2) value of $216 e^2$ fm$^4$. An extra enhancement factor of
2 is needed to reproduce the inelastic scattering cross section consis-
tent with Ref. 1. The result of this calculation is shown in Fig.26-1 and
yields an excellent description of the experimental data. Also the
pronounced forward angle minima found experimentally are well described.

In Fig. 26-2 the different contributions to the cross section are
shown separately. The nuclear excitation (broken line) yields an
angular distribution which is similar to those found from nuclear
transfer reactions with heavy ions (see section 24 ). It
also shows the forward angle oscillations discussed above. The dot-
dashed line shows the angular distribution assuming pure Coulomb
excitation. It shows a big maximum at about $22^\circ$ which gives rise to
the well known Coulomb-nuclear interference structure. However, the pure Coulomb excitation angular distribution also shows a diffraction structure. The amplitude for Coulomb-excitation has another maximum at angles of about 11°, the phase of which is opposite to that for nuclear excitation. This enhances the 11° minimum which is present in the diffraction pattern of the pure nuclear excitation and thus yields a very good fit to the data. Calculations have also been performed with conventional complex form factors. However the shape of the experimental angular distribution is not fitted as well by these calculations. The fact that the microscopic form factor calculations give a good fit to the data and, in particular, are able to reproduce the Coulomb-nuclear interference effects indicates that the radial dependence of the form factor is perhaps better described in the microscopic model \((f(r) \sim e^{-\alpha r})\) than by the derivative of an optical potential of Woods-Saxon shape.

References

Fig. 26-1. Differential Cross Sections for Elastic and Inelastic Scattering of $^{16}\text{O}$ on $^{30}\text{Si}$. 

$^{16}\text{O} + ^{30}\text{Si}$

$E_{^{16}\text{O}} = 60 \text{ MeV}$

$d\sigma/d\Omega$ [mb/sr]

Elastic

$2^+$

$E_x = 2.24 \text{ MeV}$

$\theta_{\text{CM}}$

Fig. 26-1. Differential Cross Sections for Elastic and Inelastic Scattering of $^{16}\text{O}$ on $^{30}\text{Si}$. 
Fig. 26-2. Nuclear and Coulomb Contributions to the Inelastic Scattering Cross Section.
27. **Elastic and Inelastic Scattering of $^{16}$O on the Even Sm Isotopes**

D. Weber, J. L. Artz, V. Shkolnik, D. Dehnhard, and N. M. Hintz

A study of interference phenomena between the Coulomb and the nuclear interaction with complex nuclei may provide a better understanding of the nuclear interaction. Last year we reported on a preliminary study\(^1\) of elastic and inelastic scattering of $^{16}$O from $^{152}$Sm. This year we have extended this study to even samarium isotopes from the nearly spherical $^{148}$Sm to the well-deformed $^{154}$Sm at $^{16}$O energies between 20 and 67 MeV. We hope to determine whether systematic differences occur as a result of the shape transition. In addition, we hope to investigate a second effect. Since the penetrability of heavy ions through nuclear matter is far smaller than that of light ions, $^{16}$O projectiles are expected to sample only the nuclear surface. Therefore, a difference between the deformation parameters derived in this work and those previously obtained with light ion projectiles might provide us with a test for an angular dependence of the diffuseness.

Calculations were performed with the DeBoer-Winther code\(^2\), a semi-classical coupled-channels Coulomb excitation program. A comparison of the data with the Coulomb excitation calculation shows where the onset of nuclear effects occurs and how the experimental cross sections differ from pure Coulomb excitation in the interference region. The electromagnetic multipole moments, which are inserted in the DeBoer-Winther calculations in order to fit the low energy data, provide a check on those moments previously
determined. These moments will eventually be needed for the full nuclear-Coulomb coupled-channels calculation necessary to fit the interference region. Because of the strength of the Coulomb interaction, this complete nuclear-Coulomb calculation is quite involved requiring the use of a large number of partial waves and integration steps. This part of the analysis is underway.

A beam of $^{16}$O ions was obtained from the sputter source. The size of the analyzed beam was restricted at the entrance to the scattering chamber by a 1 mm wide, 1.5 mm high defining aperture. Target thickness was typically $5 \, \mu g/cm^2$ Sm on a $10 \, \mu g/cm^2$ carbon backing. Two monitor detectors were placed in the scattering chamber at $\pm 30^\circ$(Lab) with respect to the incident beam direction. The elastic yields collected by these monitors were used for absolute normalization to the Rutherford cross sections. The scattered particles were analyzed with four position-sensitive detectors placed at the focal plane of the Enge split-pole magnetic spectrograph. These detectors collected the $5^+\,, \, 6^+\,, \, 7^+\,$, and $8^+$ charge states of $^{16}$O.

A sample spectrum for $^{154}$Sm is shown in Fig. 27-1. It is clear from the level spacing of 82 keV between the ground state and first excited state that resolution must be optimized in this work. With $^{16}$O projectiles, the principal contribution to peak width was the target thickness. The use of the very thin targets (in a reflective geometry) resulted in an optimum resolution of 35-50 keV at 50 MeV. As seen from Fig. 27-1, this was sufficient to resolve the ground state from the $2^+$ state of $^{154}$Sm.
Excitation functions were measured at $\Theta_{\text{Lab}} = 155^\circ$ from 20 MeV, well below the Coulomb barrier, to about 67 MeV, well into the region of strong absorption, for $^{148,150,152}_{\text{Sm}}$. For $^{154}_{\text{Sm}}$ data were taken from 20 MeV to 60 MeV. Angular distributions were obtained for $^{148,150,152}_{\text{Sm}}$ at 40 MeV and for $^{152}_{\text{Sm}}$ at 59 MeV, from $\Theta_{\text{Lab}} = 100^\circ$ to $155^\circ$ in $5^\circ$ steps. The data are presented in Figs. 27-2 to 27-4. Errors are smaller than the point sizes unless they are explicitly shown.

The results of the calculations with the DeBoer-Winther code are also shown in Figs. 27-2 to 27-4. The electromagnetic transition matrix elements in the calculations were adjusted so that the 40 MeV angular distributions and the low energy portions of the excitation functions would be fit. Parameter sets used in the calculations are given in Table 27-1. As seen in Figs. 27-2 through 27-4, parameter sets I, IV, and VI give good fits to the sub-Coulomb data for $^{148,150,152}_{\text{Sm}}$, respectively. Sets II and V were included to demonstrate the sensitivity of the cross sections to changes in transition parameters. The curves calculated with sets III and VII show the effect of turning off the quadrupole moment, $Q$, of the $2^+$ state (setting the $2^+ \rightarrow 2^+$ element equal to 0). As seen in the figures, fits are relatively insensitive to $Q$. The calculation with set VIII demonstrates the small effect of excluding the direct E4 excitation process for $^{152}_{\text{Sm}}$, the only isotope for which we have included E4 effects.

The parameters which give the best fits to the data for the $2^+$ states of all three isotopes agree reasonably well with those
obtained in previous light ion work\textsuperscript{3-8}. The $4^+$ and $6^+$ data for $^{152}\text{Sm}$ are not well fit, however, not even below the barrier. This indicates that previously reported matrix elements\textsuperscript{3-5} involving these states may not be applicable here. It may be, however, that nuclear effects are present even well below the Coulomb barrier\textsuperscript{9}.

Interference effects begin to appear in the excitation functions (Figs. 27-3 and 27-4) at about 54 MeV. Strong absorption takes place above 60 MeV. The effective Coulomb barrier for these deformed nuclei appears to be reduced compared with that seen\textsuperscript{10} for $^{16}\text{O}$ on the spherical $^{142}\text{Nd}$. For $^{148}\text{Sm}$ and $^{150}\text{Sm}$ in Fig. 27-3, one sees some structure in the excitation function for elastic scattering in the region of 55 to 60 MeV, but very little structure for inelastic scattering to the $2^+$ states. The $^{152}\text{Sm}$ excitation function, shown in Fig. 27-4, is qualitatively different from those of the lighter isotopes. Here a significant rise in the elastic scattering cross section above the Coulomb excitation prediction is noted in the interference region. This is accompanied by a drop in the $2^+$ strength relative to Coulomb excitation. In order to further investigate this effect, an angular distribution was taken at 59 MeV where the effect is large. These data are also shown in Fig. 27-4. The data follow the Coulomb excitation predictions quite well at forward angles where one is well below the effective Coulomb barrier. At backward angles, however, a rise in ground state cross section and subsequent drop in $2^+$ strength relative to Coulomb excitation are observed. We plan to determine whether similar behavior can be observed in $^{154}\text{Sm}$. Data analysis and calculations for $^{154}\text{Sm}$ are in progress.
References


### TABLE 27-1.

| Isotope | Parameter | \(\langle \ell_f|\hat{M}(E2)|\ell_i \rangle\), eb | M(E4) matrix |
|---------|-----------|---------------------------------|--------------|
|         | Set       | 0→2  | 2→4  | 4→6  | 6→8  | 2→2  | 4→4  | 6→6  |             |
| 148 \(\text{Sm}\) | I         | -.87  | -1.65^a | .96^b | no |
|         | II        | -.80  | -1.52^a | .96^b | no |
|         | III       | -.87  | -1.65^a | 0     | no |
| 150 \(\text{Sm}\) | IV        | -1.22 | -2.32^a | 1.61^b | no |
|         | V         | -1.17 | -2.22^a | 1.61^b | no |
| 152 \(\text{Sm}\) | VI        | -1.84 | -2.97  | -3.95 | -4.86 | 2.21^c | 3.4   | 3.60^c | yes^d |
|         | VII       | -1.84 | -2.97  | -3.95 | -4.86 | 0     | 3.4   | 3.60^c | yes^d |
|         | VIII      | -1.84 | -2.97  | -3.95 | -4.86 | 2.21^c | 3.4   | 3.60^c | no |

^a based on experimental \(B(E2;0^+ \rightarrow 2^+)\) and vibrational model

^b Ref. 8

^c based on experimental \(B(E2;0^+ \rightarrow 2^+)\) and rotational model

^d Ref. 11
Fig. 27-1. Spectrum of $^{160}$O scattered from $^{154}$Sm at 155° and 50 MeV.
Fig. 27-2. Scattering of $^{16}$O from $^{148,150,152}$Sm at $E_L = 40$ MeV as a function of angle. The parameter sets used in calculating the inelastic curves are defined in Table 27-1.
Fig. 27-3. Scattering of $^{16}$O from $^{148,150}$Sm at 155° as a function of energy. The parameter sets used in calculating the curves are defined in Table 27-1.
Fig. 27-4. Scattering of $^{16}_0$ from $^{152}_{\text{Sm}}$ at 155° as a function of energy and at 59 MeV as a function of angle. The parameter sets used in calculating the curves are defined in Table 27-1.
The most widely studied heavy ion single nucleon transfer reaction to date has been proton stripping with \(^{16}O,^{15}N\). This has been due to the relative ease of obtaining an \(^{16}O\) beam and the favorable Q value for this reaction on most targets. Since beams of the other two stable oxygen isotopes have become available, investigations of neutron stripping from heavy ion projectiles are now feasible experimentally. The present work is a preliminary survey of the \(^{18}O,^{17}O\) reaction on four targets. Matching conditions are well met for most targets because ground state Q values are typically within the range \(\pm 1.0\) MeV.

Single nucleon stripping with heavy ions is not generally expected to be more useful for nuclear spectroscopy than the corresponding light ion reactions. In fact, at Tandem energies, in many cases the identification of the L transfer from the angular distribution is impossible. Furthermore, many transitions do not involve unique L transfers. For these reasons perhaps ultimately the most productive applications of heavy ion reactions will be in multinucleon transfer. Particularly interesting will be those cases which cannot be done with light ions, for example, two proton pick-up. Nonetheless, if multinucleon transfers are to be useful, the reaction mechanism of the simpler single nucleon transfer must be understood first. To this end a comparison of the current theoretical treatment of single nucleon reactions with some new data may be worthwhile.
All heavy ion transfer stripping reactions involve simultaneously a pick-up reaction on the incoming projectile. In the (18O, 17O) reaction a feature of additional interest is the possibility of doing proton pick-up on both the (1d 5/2)^2 and the (2s 1/2)^2 components of the 18O ground state. In the latter case the outgoing 17O is left in its first excited state; a 1/2+ at 0.817 MeV. If the stripped neutron goes into the ground state of the residual nucleon in both cases, it is possible to accurately measure the relative strengths of the two components in 18O. Clearly to the extent that the treatment of the reaction mechanism is accurate, measured relative strengths should not depend on the target nucleus. Through this fact then, the data provide a test of the theoretical description of the transfer. Additionally the spectroscopic amplitudes extracted for the states observed in the residual nuclei can be compared with well known (d,p) results.

The data were taken using the split-pole spectrograph and the detection and particle identification system described in Section 36 of this report. A 50 MeV 18O beam was used to bombard targets of 28Si, 40Ca, 48Ca, and 54Fe. The calcium targets were metallic and were transferred to the scattering chamber under vacuum to minimize oxidation. The 54Fe, 40Ca, and 48Ca targets were rotated continuously in the scattering chamber to retard damage caused by the beam.

The angular distributions which were measured are shown in Figs. 28-1, 28-2, and 28-3. The curves are finite range DWBA
calculations performed with the code LOLA. The optical model parameters used in the calculations were deduced from fits to measured elastic scattering (Section 30) using the code RAROMP. Each target was fit separately, although work is now underway to determine a set of parameters which might simultaneously fit all the data.

The shapes of the angular distributions are fairly well reproduced for the two lightest targets, $^{28}$Si and $^{40}$Ca. There is, however, a tendency for the calculations to over-predict the large angle cross section. The fits for the $^{48}$Ca and $^{54}$Fe targets are noticeably worse. In particular, the calculated curve seems to be shifted towards larger angles by 6 to 8 degrees compared to the data. This effect has been observed in other heavy ion single nucleon transfer reactions. One well known way to improve the fits in these cases is to increase the diffuseness in the outgoing distorted wave optical potential. This prescription does improve the fit in the case of the ($^{18}$O, $^{17}$O) reactions measured here. However, the increase in the diffuseness needed ($\sim$60%) to improve the fit to the transfer data completely destroys the fit to the elastic scattering. Although this empirical procedure may have some qualitative significance, it represents a rather drastic departure from the spirit of the DWBA. Since this work is intended in large part as a test of the DWBA, such an approach should be avoided.

Despite the fact that the shapes are not always well reproduced, it is possible to some degree to normalize the calculations to the data, and thus to extract the product of the spectroscopic factors
for pick-up from the projectile and stripping onto the target. Fig. 28-1 shows six angular distributions for stripping to the ground states of the nuclei $^{29}\text{Si}$, $^{41}\text{Ca}$, and $^{49}\text{Ca}$. The reactions on the left side of the drawing involved the outgoing $^{17}\text{O}$ in its ground state while for those on the right side the $^{17}\text{O}$ was in its first excited state. The six measured angular distributions and the six corresponding DWBA calculations can be used to obtain three independent values for the ratio of the $^{17}\text{O}_{\text{g.s.}}$ $C^2S$ to the $C^2S$ for the first excited state. These ratios are listed in Table 28-1. The table also includes some values for this ratio from light ion reaction studies.

If a $C^2S$ is known or assumed for $^{18}\text{O} - n \rightarrow ^{17}\text{O}_{\text{g.s.}}$, then $C^2S$'s can be extracted for the states observed in the heavy products. Table 28-2 lists a $C^2S$ for all the states shown in Figs. 28-1, 28-2, and 28-3 assuming a value of 1.5 for $^{18}\text{O} - n \rightarrow ^{17}\text{O}_{\text{g.s.}}$. Also shown are the values of $C^2S$ for the same states as derived from $(d,p)$ studies.

While the absolute $C^2S$'s are significantly different from the light ion results, it appears that the relative values for states in $^{29}\text{Si}$, $^{41}\text{Ca}$, and $^{55}\text{Fe}$ are in better agreement with the other work. (Except for the $5/2^+$ state in $^{79}\text{Si}$.)

Although the analysis presented here is preliminary, it does appear so far that the DWBA is not quite capable of reproducing either the shape or the magnitude of the measured angular distributions, especially for the heavier targets.
Table 28-1.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>C$^2$S $^{17}<em>{0\text{g.s.}}$ d$</em>{5/2}$/C$^2$S $^{17}_{0}$ 0.817 MeV s$^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}<em>{\text{Si}}$($^{18}</em>{\text{O}}$, $^{17}<em>{0}$)$^{29}</em>{\text{Si}}$</td>
<td>16.3</td>
</tr>
<tr>
<td>$^{40}<em>{\text{Ca}}$($^{18}</em>{\text{O}}$, $^{17}<em>{0}$)$^{41}</em>{\text{Ca}}$</td>
<td>21.1</td>
</tr>
<tr>
<td>$^{48}<em>{\text{Ca}}$($^{18}</em>{\text{O}}$, $^{17}<em>{0}$)$^{49}</em>{\text{Ca}}$</td>
<td>6.5</td>
</tr>
<tr>
<td>$^{18}<em>{\text{O}}$(p,d)$^{17}</em>{0}$ 1)</td>
<td>7.1</td>
</tr>
<tr>
<td>$^{18}<em>{\text{O}}$(d,t)$^{17}</em>{0}$ 2)</td>
<td>5.3</td>
</tr>
<tr>
<td>$^{18}<em>{\text{O}}$(p,d)$^{17}</em>{0}$ 3)</td>
<td>10.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Residual Nucleus</th>
<th>Final State</th>
<th>$C^2S$ $^1$</th>
<th>(relative) $^2$</th>
<th>$C^2S$ from (d,p) $^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{29}\text{Si}$</td>
<td>g.s. $1/2^+$</td>
<td>1.5</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>1.27 MeV $3/2^+$</td>
<td>1.6</td>
<td>.56</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>2.03 MeV $5/2^+$</td>
<td>1.9</td>
<td>.68</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>3.62 MeV $7/2^-$</td>
<td>1.3</td>
<td>.46</td>
<td>0.38</td>
</tr>
<tr>
<td>$^{41}\text{Ca}$</td>
<td>g.s. $7/2^-$</td>
<td>1.8</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.94 MeV $3/2^-$</td>
<td>1.1</td>
<td>.64</td>
<td>.85</td>
</tr>
<tr>
<td></td>
<td>2.46 MeV $3/2^-$</td>
<td>.30</td>
<td>.17</td>
<td>.26</td>
</tr>
<tr>
<td></td>
<td>3.94 MeV $1/2^-$</td>
<td>1.6</td>
<td>.90</td>
<td>.70</td>
</tr>
<tr>
<td>$^{49}\text{Ca}$</td>
<td>g.s. $3/2$</td>
<td>0.63</td>
<td></td>
<td>1.02</td>
</tr>
<tr>
<td>$^{55}\text{Fe}$</td>
<td>g.s. $3/2^-$</td>
<td>0.58</td>
<td>.81</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>0.44 MeV $1/2^-$</td>
<td>0.49</td>
<td>.68</td>
<td>0.60</td>
</tr>
</tbody>
</table>

$^1$ Assuming $^{17}\text{O}$ g.s. $C^2S = 1.5$

$^2$ Fixing g.s. $C^2S$ to (d,p) result

$^3$ Average value from known d,p results:

- Nuclear Data Sheets B4 (1970)
- Nuclear Data Sheets B3 (1970).
\[ \left( ^{18}O, ^{17}O \text{(g.s.,} 5/2^+) \right) \]
\[ E_{^{18}O} = 50 \text{ MeV} \]

\[ ^{29}\text{Si(g.s.,} 1/2^+) \]
\[ \Delta L = 2 \]

\[ ^{40}\text{Ca(g.s.,} 7/2^-) \]
\[ \Delta L = 5, 4, 3, 2, 1 \]

\[ ^{49}\text{Ca(g.s.,} 3/2^-) \]
\[ \Delta L = 3, 2, 1 \]

\[ \left( ^{18}O, ^{17}O \text{(0.817 MeV,} 1/2^+) \right) \]
\[ E_{^{18}O} = 50 \text{ MeV} \]

\[ ^{29}\text{Si(g.s.,} 1/2^+) \]
\[ \Delta L = 0 \]

\[ ^{40}\text{Ca(g.s.,} 7/2^-) \]
\[ \Delta L = 3 \]

\[ ^{49}\text{Ca(g.s.,} 3/2^-) \]
\[ \Delta L = 1 \]

\[ \theta_{\text{c.m.}} \text{(degrees)} \]

Fig. 28-1
$^{28}\text{Si}(^{18}\text{O, }^{17}\text{O.g.s.) }^{29}\text{Si}$

$E_{^{18}\text{O}} = 50\text{ MeV}$

Fig. 28-2
$^{54}\text{Fe}(^{18}\text{O}, ^{17}\text{O}, \text{g.s.})^{55}\text{Fe}$

$E_{^{18}\text{O}} = 50 \text{ MeV}$

g.s., $3/2$

$\Delta L = 3, 2, 1$

$0.441 \text{ MeV}, 1/2^-$

$\Delta L = 3, 2$

Fig. 28-3
Further analysis of the data from the previously reported study\(^1\) of the low lying two-particle states in \(^{18}\text{O}\) with the \(^{17}\text{O}(d,p)^{18}\text{O}\) reaction has been carried out. In order to generate optical potentials for the deuteron channel to be used in the DWBA calculation of the \(^{17}\text{O}(d,p)^{18}\text{O}\) reaction, we have performed optical-model analyses of our measured elastic scattering \(^{17}\text{O}(d,d)\) data by means of the computer codes RAROMP\(^2\) and SNOOPY\(^3\). Two sets of optical-model parameters from this search were found which fit our \(^{17}\text{O}(d,d)\) data very well, as shown in Fig. 29-1. They are listed in Table 29-1 as sets D1 and D2. Also listed are two sets of proton parameters, P1 (Ref. 4) and P2 (Ref. 5), which best reproduce the experimental shapes when used in the DWBA calculations with the code DWUCK\(^6\). Fig. 29-2 illustrates the changes produced in the DWBA shape of a pure \(\ell = 0\) transition by the use of some different combinations of the optical-potential parameters of Table 29-1. A comparison of the curve produced by use of the combination P2-D1 with that produced by use of the combination P2-D2 illustrates the change in DWBA shape which can result when two different deuteron parameter sets are used, each of which fits the \(d + ^{17}\text{O}\) elastic scattering data (see Fig. 29-1). Although the use of the combination P2-D1 gives reasonable DWBA shapes for \(\ell = 0\) transitions, the \(\ell = 2\) angular distributions are less well reproduced. We therefore used the
combination P1-D1, which gives somewhat poorer \( \ell = 0 \) shapes (see Fig. 29-2) but yields the best overall agreement with all the experimental data.

The spectroscopic factors \( S \) extracted from our \( {}^{17}\text{O}(d,p) \) data with a DWBA analysis show significant differences from earlier work\(^7,8\) using the PWBA; however, our spectroscopic factors are mostly in reasonable agreement with those from\(^9\) a DWBA analysis of \( {}^{17}\text{O}(^3\text{He},d){}^{18}\text{F}(T=1) \). Comparisons with theoretical calculations for transitions to positive-parity states in \( {}^{18}\text{O} \) show a distinct preference for the weak-coupling model\(^10\) (Fig. 29-3). This preference for the weak-coupling calculation suggests that correlations involving the \( 1d_{3/2} \) and \( 1p_{3/2} \) orbitals are important.

Diagonal matrix elements of the effective neutron-neutron interaction were deduced from the data for the \( (d_{5/2})^2 \) \(^0+\), \(^2+\), \(^4+\) and \( (d_{5/2}s_{1/2})^2 \) \(^2+\), \(^3+\) configurations. A theoretical estimate of the errors involved is in qualitative agreement with the deviations observed between experiment and theory. Details of this study are discussed in Ref. 11.

References

1. T. K. Li, D. Dehnhard, and R. E. Brown, John H. Williams Laboratory of Nuclear Physics Annual Report, 1974, p. 35.


6. P. D. Kunz, private communication.


Table 29-1. Optical-Model Parameters. The combination P1-D1 was used in the DWBA calculations of this work.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Set</th>
<th>$V_R$ (MeV)</th>
<th>$r_R$ (fm)</th>
<th>$a_R$ (fm)</th>
<th>$4W_D$ (MeV)</th>
<th>$W_S$ (MeV)</th>
<th>$r_I$ (fm)</th>
<th>$a_I$ (fm)</th>
<th>$V_{so}^a$ (MeV)</th>
<th>$r_{so}$ (fm)</th>
<th>$a_{so}$ (fm)</th>
<th>$r_c$ (fm)</th>
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<tbody>
<tr>
<td>proton</td>
<td>P1</td>
<td>51.5</td>
<td>1.04</td>
<td>0.67</td>
<td>32.4</td>
<td>1.7</td>
<td>1.17</td>
<td>0.52</td>
<td>6.2</td>
<td>1.01</td>
<td>0.75</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>50.1</td>
<td>1.10</td>
<td>0.74</td>
<td>22.4</td>
<td>0</td>
<td>1.30</td>
<td>0.66</td>
<td>4.25</td>
<td>0.90</td>
<td>0.52</td>
<td>1.30</td>
</tr>
<tr>
<td>deuteron</td>
<td>D1</td>
<td>85.18</td>
<td>1.18</td>
<td>0.72</td>
<td>20.8</td>
<td>0</td>
<td>1.73</td>
<td>0.75</td>
<td>4.58</td>
<td>0.75</td>
<td>0.18</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>85.14</td>
<td>1.15</td>
<td>0.74</td>
<td>14.8</td>
<td>0</td>
<td>1.55</td>
<td>1.04</td>
<td>4.53</td>
<td>0.92</td>
<td>0.74</td>
<td>1.30</td>
</tr>
</tbody>
</table>

\(a\) The spin-orbit well depth $V_{so}$ must be multiplied by a factor of 4 for protons and by a factor of 2 for deuterons before being entered into DWUCK4.

\(b\) Ref. 4.

\(c\) Ref. 5.

\(d\) this work.
Fig. 29-1. $^{17}\text{O}(d,d)^{17}\text{O}$ differential cross sections $\sigma$ plotted as the ratio to the Rutherford cross section $\sigma_R$. The lines show the results of the optical-model calculations using the indicated parameter sets of $\varepsilon 29-1$. 

$E_d = 18 \text{ MeV}$
Fig. 29-2. Comparison of DWBA curves for the pure $l = 0$ transition $^{17}O(d,p)^{18}O(5.372$ MeV) using the indicated combinations of the optical potential parameter sets of Table 29-1.
Spectroscopic factors $S$ from $^{17}\text{O}(d,p)^{18}\text{O}$

Fig. 29-3. Spectroscopic factors $S$ from the $^{17}\text{O}(d,p)^{18}\text{O}$ reaction compared with the theoretical predictions of the weak-coupling model [Ref. 10].
30. Elastic Scattering of $^{18}O$ on $^{28}Si$, $^{40}Ca$, $^{48}Ca$, $^{54}Fe$, and $^{58}Ni$

J. L. Artz, D. Dehnhard, D. A. Lewis, T. K. Li, H. P. Morsch
J. F. Petersen, V. Shkolnik, and D. J. Weber

Elastic scattering of $^{18}O$ on $^{28}Si$, $^{40}Ca$, $^{48}Ca$, $^{54}Fe$, and $^{58}Ni$ was measured at 50.0 MeV in order to obtain optical model parameters for reactions involving one- and two-nucleon transfers and inelastic scattering described elsewhere in this Progress Report. Fig. 30-1 shows the corresponding cross sections given as ratios to the Rutherford cross sections, as well as some preliminary fits obtained with the optical model program RAROMP. Table 30-1 lists the optical model parameters deduced from the fits in Fig.30-1.

<table>
<thead>
<tr>
<th>Target</th>
<th>U</th>
<th>$R_{or}^*$</th>
<th>Ar</th>
<th>W</th>
<th>$R_{ow}^*$</th>
<th>Aw</th>
</tr>
</thead>
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<tr>
<td>$^{28}Si$</td>
<td>60</td>
<td>1.20</td>
<td>.529</td>
<td>15.5</td>
<td>1.14</td>
<td>.728</td>
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<tr>
<td>$^{40}Ca$</td>
<td>61.8</td>
<td>1.24</td>
<td>.528</td>
<td>8.27</td>
<td>1.27</td>
<td>.727</td>
</tr>
<tr>
<td>$^{48}Ca$</td>
<td>97.0</td>
<td>1.21</td>
<td>.497</td>
<td>59.7</td>
<td>1.14</td>
<td>.422</td>
</tr>
<tr>
<td>$^{54}Fe$</td>
<td>66.8</td>
<td>1.21</td>
<td>.531</td>
<td>41.6</td>
<td>1.20</td>
<td>.585</td>
</tr>
<tr>
<td>$^{58}Ni$</td>
<td>71.6</td>
<td>1.22</td>
<td>.510</td>
<td>32.8</td>
<td>1.23</td>
<td>.578</td>
</tr>
</tbody>
</table>

$^*_R = R_o (A_T^{1/3} + A_p^{1/3})$
Elastic Scattering of $^{18}$O at 50.0 MeV

- $^{28}$Si
- $^{40}$Ca
- $^{48}$Ca
- $^{54}$Fe
- $^{58}$Ni

$\sigma/\sigma_R$ vs. $\Theta_{cm}$
In the study of heavy ion inelastic scattering one encounters several new features not found in similar studies with light ions. For instance the comparatively strong Coulomb forces often cause dramatic Coulomb-nuclear interference patterns which are much more pronounced than those in light ion work\(^1\). Furthermore, since the deBroglie wave lengths are normally much smaller than the classical impact parameter, the shapes of the interference patterns can usually be understood using semi-classical pictures\(^2\).

One of the most interesting features is that it is possible to measure transitions to excited states in both target and projectile. For instance we have measured cross sections for excitation of the first \(2^+\) state in \(^{18}\)O and in \(^{58}\)Ni in \(^{18}\)O + \(^{58}\)Ni scattering. Since these two states have about the same excitation energies, the dynamics of the two reactions will be essentially the same, i.e. in a semi-classical model the trajectories will be almost identical, or in terms of the DWBA, the sets of distorted waves will be almost identical. Therefore any differences in the reaction cross sections is directly due to the structure of the nuclear states.

Previously heavy ion inelastic scattering has been analyzed in terms of a macroscopic model in which the level populated is assumed to be collective state with a deformed shape. In the usual procedure one uses a deformed optical model potential for the interaction responsible for the transition. This results in a form factor which is simply the derivative of the optical potential. This is a reasonable
assumption in cases for which the projectile is much smaller than the target, but is quite unjustified for cases in which the projectile is comparable to or larger than the target.

There are two approaches which eliminate these projectile size problems in a natural way. They are discussed in the next section.

Theoretical Descriptions

A. Folding Model

In the collective model description of $^{18}_0$O and $^{58}_0$Ni, the first $2^+$ state is characterized as having a quadrupole shape. If the equilibrium matter density is $\rho_o(r) = f(r-R_0)$, then in general the density distribution for a quadrupole shape will be

$$\rho(r) \cong f(r - R_0) [1 + \sum_{\mu} \alpha_{\mu} Y_{2\mu}]$$

$$\cong f(r - R_0) - R_0 \sum_{\mu} \alpha_{\mu} Y_{2\mu} f'(r - R_0)$$

for small deformations. The interaction potential between a finite size projectile $A$ and target $B$ is

$$V_{AB}(\vec{R}) = \int \rho_A(\vec{r}_A) \rho_B(\vec{r}_B) g(\vec{R} - \vec{r}_A - \vec{r}_B) d^3r_A d^3r_B$$

where $g$ is the nucleon-nucleon interaction. Substitution of equation 1 into equation 2 leads to four terms in the folded potential which describe elastic scattering, projectile excitation, target excitation, and simultaneous excitation of both target and projectile.

A computer program FOLDER was written to calculate the integral in equation 2. The matter densities $\rho_A$ and $\rho_B$ are parameterized in

*Exchange effects are ignored in this expression. However because of strong absorption only the surface region is important. In the surface region the density is low and exchange effects are presumably small.
either the harmonic oscillator or two parameter fermi forms commonly used to describe charge distributions obtained from electron scattering. The nucleon-nucleon interaction $g$ may be either a Coulomb potential or a Gaussian. The Coulomb and nuclear form factors are calculated separately and added together later.

B. Microscopic Model

A shell model description is also applied to the data in which a renormalization of the effective interaction due to core polarization is used. Such an approach was found to give an excellent description of low lying quadrupole excitations in (sd) and $f_{7/2}$ shell nuclei for $^3$He and $\alpha$ scattering consistent with electromagnetic transitions rates. The transition form factor $\langle f | V | i \rangle$ is approximated by $N \langle f_s | V_s | i_s \rangle$ where $\langle i \rangle$ and $\langle f \rangle$ are the true nuclear wave functions, $\langle i_s \rangle$ and $\langle f_s \rangle$ are simpler shell model wave functions, and $N$ can be considered as a renormalization of the effective interaction $V_s$ which is dependent on the shell model wave functions $\langle i_s \rangle$ and $\langle f_s \rangle$. This is similar to the use of effective charges in the calculation of electromagnetic transitions. For isoscalar contributions which are dominant in the transitions of interest the renormalization factor $N$ may be related to the effective charges by $N = N^*_{\text{eff}}$. The extra enhancement $N^*$ for inelastic excitations is mainly due to the fact that the electromagnetic transition operator involves only proton core polarization components whereas in inelastic scattering both proton and neutron core polarization components contribute; this would give an $N^*$ of about 2. Also other effects are included, e.g. contributions from the exchange character of the nucleon-nucleon interaction. From
the results of ref. 1, \( N^* \) is exactly 2 if a volume integral of the nucleon-nucleon interaction of 446 MeV fm\(^3\) is used; this volume integral is consistent with that of interactions describing few nucleon systems\(^5\). It should be noted that this extra enhancement is reproduced in a shell model calculation\(^6\) in which many NN core polarization components are taken into account explicitly (without the inclusion of exchange effects).

**Comparison with Experimental Data**

The inelastic scattering data were taken using the detection and particle identification system described elsewhere in this report (Section 36). A 50 MeV \(^{18}\)O beam was used to bombard enriched targets of \(^{40}\)Ca, \(^{48}\)Ca, \(^{54}\)Fe, and \(^{58}\)Ni. The calcium targets were metallic and were transferred to the scattering chamber under vacuum to minimize oxidation. All four targets were continuously rotated in the scattering chamber to reduce damage caused by the beam. Angular distributions typically in the range 16° to 50° lab angle were obtained for the first 2\(^+\) state in the targets \(^{48}\)Ca, \(^{54}\)Fe, and \(^{58}\)Ni. The excitation of the \(^{18}\)O 2\(^+\) state at 1.98 MeV was observed with all four targets. At present only the \(^{18}\)O + \(^{58}\)Ni and \(^{18}\)O + \(^{48}\)Ca data have been analyzed.

The elastic and inelastic data for the scattering of \(^{18}\)O from \(^{58}\)Ni is shown in Fig. 31-1. The cross section for the simultaneous excitation of the first 2\(^+\) states in both nuclei was too small to be measured (less than \(\sim 50 \mu b/sr\)). The Coulomb-nuclear interference minimum for projectile excitation is much deeper and occurs at a smaller scattering angle. Also the forward angle structure is more
pronounced for projectile excitation than for target excitation. These characteristics (found also in $^{18}_0 + ^{54} _{Fe}$ scattering) can be understood in a semiclassical picture and are qualitatively reproduced by the DWBA using folding and microscopic model form factors.

The Coulomb form factors for the folding model were computed using nuclear charge distributions taken from an analysis of electron scattering data. Since $^{18}_0$ and $^{58}_{Ni}$ have about the same number of neutrons as protons, the same shapes were used for the nuclear matter distributions in the computation of the folded nuclear form factors. The nucleon-nucleon interaction used (a gaussian with a range of 1.67 fm and a volume integral of 446 MeV - fm$^3$) is consistent with those used in few nucleon problems. Since, at radii far outside of the nuclear surface the form factor must have the form

$$\frac{4\pi}{5} \frac{Ze}{r^3} [B(E2)]^{1/2}$$

where Ze is the charge of the particle which is not excited, the previously measured B(E2) transition rates ($657. e^2 fm^4$ for $^{58}_{Ni}$-ref. 7, $86. e^2 fm^4$ for $^{48}_{Ca}$-ref. 8, and $37.6 e^2 fm^4$ for $^{18}_0$-ref. 9) provide an absolute normalization for the form factors.

The distorted waves used in the inelastic scattering calculations were generated with the parameters listed in Table 30-1. For the calculations with folded form factors it would be more consistent to use a folding model potential (incorporating a complex nucleon-nucleon interaction) which fits the elastic scattering, to produce the distorted waves. However, at present, no calculations of this type has been made.
For the microscopic form factors, an effective nucleon-nucleon potential with a range of 2.06 fm was used. This results from combining the $^3\text{He}$-nucleon interaction of ref. 4 with the recent $^3\text{He}$ internal wave function of ref. 10. The effective potential was then folded with nuclear densities from electron scattering. Details of the present calculations are similar to those in ref. 4. Simple valence particle wave functions of the form $(d_{5/2})^2$, $(f_{7/2} p_{3/2})^2$, and $(p_{3/2})^2$ were used for $^{18}\text{O}$, $^{48}\text{Ca}$, and $^{58}\text{Ni}$ respectively. To obtain the experimental $B(E2)$ values listed above for these nuclei, effective neutron charges $e_n = 0.91$ for $^{18}\text{O}$, $e_n = 0.74$ for $^{48}\text{Ca}$, and $e_n = 2.60$ for $^{58}\text{Ni}$ were required. A value of $N^* = 2$ (consistent with the results of ref. 4) was used for $^{18}\text{O}$ and for $^{58}\text{Ni}$ excitation. For the excitation of the $2^+$ state in $^{48}\text{Ca}$ a value of $N^* = 1.8$ is used. In a similar calculation for inelastic $\alpha$ scattering this slightly smaller value is found to give the correct $^{48}\text{Ca} 2^+$ excitation strength.

The form factors for $^{18}\text{O} + ^{58}\text{Ni}$ scattering are shown in Fig. -2. The Coulomb part of the form factors is comparatively strong for $^{50}\text{Ni}$ excitation which causes the node to occur at a smaller radius. This is consistent with the fact that the Coulomb nuclear interference minimum occurs at a larger scattering angle for $^{58}\text{Ni}$ excitation. The nuclear parts of the microscopic form factors have a somewhat larger radial extent. Since the reactions are surface peaked this enhances the nuclear contribution to the cross sections causing the Coulomb nucleon interference to occur at a smaller scattering angle and the radial node to more to a larger radius. The DWBA results using these form factors reproduce the overall cross sections and qualitative
features of the data fairly well although the detailed fit in the Coulomb-nuclear interference region is rather poor.

The predictions of the microscopic model fit the data for \( ^{18}_0 + ^{48}_\text{Ca} \) scattering rather well (Fig. 31-3). Folding model calculations have not been made for this case yet. A comparison of the form factors used with the corresponding form factor for \( \alpha \) scattering is shown in Fig. 31-4 to emphasize the consistency of the approach. The form factors show a large difference between light and heavy ion scattering which is mainly due to large differences in the effective interaction. In spite of these large differences and the fact that the dynamics of the process is also very different for light and heavy ions, the results of our microscopic description (using the same nucleon-nucleon interaction for \( ^{3}_\text{He}, \alpha \) and heavy ion scattering) are in remarkably good agreement with our data.

One possible explanation for the poor fits to the \( ^{18}_0 + ^{58}_\text{Ni} \) data is that the nuclear part of the form factor should be complex. In fact it was suggested\(^{12}\) some time ago that careful measurement of the Coulomb-nuclear interference minimum would allow one to determine the phase of the effective interaction. Consequently a search was made in which the magnitude and phase of the nuclear form factors were varied. The results were that it was possible to obtain better fits for \( ^{18}_0 \) excitation and good fits for \( ^{58}_\text{Ni} \) excitation; in particular the correct angular position of the Coulomb nuclear interference minimum could be reproduced. However for \( ^{18}_0 \) excitation a phase of \( \sim 70^\circ \) was required whereas \( ^{58}_\text{Ni} \) excitation needed a phase of \( \sim 30^\circ \). Since the open channels are almost the same for the two cases, one would expect that about the same phase would be needed for both.
inelastic channels. Furthermore with a phase angle of $70^\circ$, the
predicted shape for the $^{18}_0$ Coulomb nuclear interference minimum
was much too shallow and the strength of the nucleon-nucleon potential
had to be drastically reduced. Consequently, at present, it appears
that the use of an effective nucleon-nucleon interaction with a
variable phase provides only a means of parameterizing the data, and
that other effects (probably multistep processes) must be included for
an adequate description of the $^{18}_0 + ^{58}_{\text{Ni}}$ data.

References
   125 (1974).
Fig. 31-1. Elastic and Inelastic Distributions for $^{18}\text{O} + ^{58}\text{Ni}$. 
Fig. 31-2. Microscopic and Folding Form Factors for $^{18}O + ^{58}Ni$. 
Fig. 31-3. Elastic and Inelastic Angular Distributions for $^{18}$O + $^{48}$Ca.
Fig. 31-4. Microscopic and Folding Form Factors for $^{18}$O + $^{48}$Ca.
Two-Nucleon Transfer With Heavy Ions

J. F. Petersen, D. A. Lewis, H. P. Morsch
D. Dehnhard, T. K. Li, B. Bayman

The study of two-nucleon transfer (2NT) reactions induced by light ions has been pursued for many years. In particular, it has been seen that 2NT data are capable of giving information about the coherence properties of the different constituents of a given state. Furthermore, the selectivity of many 2NT reactions can often be used to probe the structure of states rather high in excitation, where the density of states limits the usefulness of single nucleon transfer reactions.

In view of the successes with light ions, it is natural to consider doing 2NT with heavy ions. As has been the case with single nucleon transfer, using heavy ions introduces some significant complications. For heavy ion induced reactions it is clear that zero range DWBA is not adequate, and there are indications that for many transitions a CCBA analysis may be necessary. For light ion two proton or two neutron transfers, the transferred nucleons can be assumed to always be in a relative S state, since this is their structure in the light ion projectile. This leads to the simple and useful selection rule that the L transfer equals the J of the final state. On the other hand, for many heavy ion projectiles the two protons or neutrons may have relative S of 0 or 1. This, of course, eliminates the identification of J with L. On the other hand, the addition of \( S = 1 \) components permits the possibility of a richer spectroscopy, especially when the heavy ion results can be compared with analogous light ion data. Perhaps one of the most exciting possibilities is the capability for doing 2NT reactions which can-
not be done with light ions. Consider, for example, the two proton pickup reaction \((^{18}_0, ^{20}_N)\), whose light ion analog, \((n, ^3\text{He})\), is virtually impossible experimentally.

In the past year a program to measure heavy ion induced 2NT's has been underway. Efforts have centered on the use of an \(^{18}_0\) beam, since to date relatively few 2NT reactions have been studied using this projectile. It was felt that a very basic and important reaction would be the two neutron stripping \((^{18}_0, ^{16}_O)\) on the doubly magic nucleus \(^{48}\text{Ca}\). This case should be an important test of our understanding of the reaction mechanism, since complications due to both nuclear structure and coupled channel effects might reasonably be thought to be minimized. Fig. 32-1 shows angular distributions obtained for four states in \(^{50}\text{Ca}\). Currently only the finite range DWBA for the ground state transition has been completed. For this calculation, the wave function for the two neutrons in the initial \(^{18}_0\) state was taken to be:

\[
0.893(1d_5/2)^2 + 0.354(2s1/2)^2 + 0.278(1d_3/2)^2
\]

while in \(^{50}\text{Ca}\) a pure \((2p3/2)^2\) configuration was used. It is interesting to note that the "Unhappiness factor" (the factor by which the calculated curve must be multiplied to give agreement with the data) is only 8. For most other heavy ion 2NT observed and analyzed so far, this factor has been much larger: typically a value of from 30 to 100 is needed. This result then seems to confirm the special simplicity of this particular transition.

Fig. 32-2 shows an angular distribution for the two proton pickup reaction \(^{54}\text{Fe}(^{18}_0, ^{20}_\text{Ne})^{52}\text{Cr}\). Analysis of this transition has not been started yet, but the data are shown here as a demonstration of the feasibility of measuring this very interesting reaction.
Fig. 32-1
$^{54}\text{Fe}(^{18}\text{O},^{20}\text{Ne})^{52}\text{Cr}$

$E_{^{18}\text{O}} = 50$ MeV

d$\sigma$/d$\Omega$ mb/sr vs. $\theta_{\text{c.m.}}$ (degrees)

g.s., $O^+$
V. HYPERFINE AND X-RAY EXPERIMENTS

33. Optical Isotope Shift Experiments
M. E. Cage, J. H. Broadhurst, D. L. Clark,
G. W. Greenlees, and D. A. Lewis

This program uses Doppler-free laser techniques to study nuclear properties via measurements of atomic hyperfine structure. At present, effort is concentrated on measurements of the scattering of tunable dye laser light from a well collimated atomic beam as a function of frequency. Large resonant-scattering cross sections are observed whenever the laser frequency corresponds to a transition in the atoms. A detailed description of the method can be found in last year's Progress Report.

The technique is characterized by both high resolution and high sensitivity. The resolution is in general comparable to natural line widths and the sensitivity, occasioned by the high resonant scattering cross section (~10^{-10} \text{ cm}^2 or ~10^{14} \text{ barns}!), means that relatively few atoms are needed for a measurement.

The initial objective of the work is to obtain information on nuclear charge sizes via measurement of optical isotope shifts. The very high sensitivity makes measurements feasible for unstable atomic species produced on-line with the accelerator. This is an area of nuclear size measurement which is not accessible to other techniques such as \( \mu \)-mesic atoms and electron scattering.

Measurements using natural ytterbium beams, reported in last year's Progress Report, demonstrated the feasibility of the method. This work was published in J. Phys. B7, L513 (1974). These results
show factors of 100 improvement in resolution and counting rate compared to previous measurements on Yb. Using natural Yb the peak due to the 0.14% abundant $^{168}$Yb component was easily resolved from other components present even though the transition probability of the $^1S_0 - ^3P_1$ intercombination line used at $5556 \, \text{Å}$ was a factor of 100 smaller than that for resonant transitions. It is estimated that when observing resonant transitions, such as the 5535 Å line of Ba, that the recorded signals due to scattered photons contain contributions from every atom in the atomic beam even though it is necessary to work at reduced laser intensity to avoid power-broadening effects.

Despite the success of the Yb results it was clear that significant improvements could be made on the initial arrangement. The atomic beam chamber used was a modified evaporator. This had many shortcomings, the principle ones being high light backgrounds and relatively poor vacuum. The photomultiplier detector used with this arrangement was operated in the current mode. A new chamber has been constructed with high vacuum capabilities and improved optics, making single photon counting possible and greatly improving the signal-to-noise ratio.

Although the resolution obtained with Yb showed two orders of magnitude improvement over previous data, the isotope shifts obtained showed only one order of magnitude improvement in accuracy. This was due to variations in the marker spacings and non-linearities in the scanning system. The marker spacing variations were correlated
with atmospheric pressure variations due to the etalon length being stabilized at 6328 Å whereas the markers were generated at 5556 Å. This problem has been circumvented by enclosing the etalon in a vacuum tight container and operating it in either a constant air-density environment or in vacuum. The xy recorder is being replaced by a computer recording system which will enable simultaneous recording of several parameters, making a more sophisticated analysis of the data possible.

The peak widths obtained for Yb (17 MHz FWHM) were due to the dye laser bandwidth. The addition of a vibration isolator to the dye flow system did not produce the anticipated improvement. Fluctuations due to pulsations in the dye flow were evidently being partially compensated by a feedback system already in use on the laser. The laser bandwidth is correlated with mechanical vibrations and efforts are underway to reduce these effects.

A second dye flow system, containing rhodamine 6G and water, has been installed. This extends the operation of the dye laser to the region between 5450 Å and 6250 Å.

Unlike Yb, several of the elements of interest in this work have a large number of transitions which are accessible, and in some cases as many as 100 of them show isotope shifts. These transitions are closely spaced in wavelength and therefore some relatively simple method is needed to identify lines separated by as little as 0.25 Å. Commercial instruments capable of this resolution tend to be large, expensive, and time consuming to operate. A simple fringe comparator system has thus been developed which performs the task quickly and accurately.
These various improvements are described in more detail below.

1. The Scattering Chamber

The dye laser beam scattering chamber, atomic beam oven and scattered light collection optics have been designed and built to minimize background light and maximize sensitivity. A schematic drawing of the chamber is shown in Figs. 33-1,2. The system has been designed for very high vacuum and is primarily made of non-magnetic stainless steel, with copper vacuum seals on all but a few connections. Maximum pumping speed has been compromised in the design of the light baffles, which not only reduce pumping speed but also are made with chemically blackened brass. Baffles in the atomic beam tube and a cylindrical baffle around the light collection optics also are chemically blackened brass. A portable turbo-molecular pumping module roughs out the chamber to approximately $5 \times 10^{-5}$ torr, enabling the Granville-Phillips Electro-ion pump to then evacuate the chamber to high vacuum. The ultimate pressure of the apparatus is $6 \times 10^{-9}$ torr.

The Electro-Ion Pump electronic control unit has been modified to allow the electron injectors, used to ionize noble gases, and/or the titanium sublimator to be turned off. Both are sources of light background during data collection. With the pump off, the pressure in the system shows a slow rise but allows sufficient time for dozens of data sweeps of the laser.

The atomic beam oven has been designed to evaporate materials while minimizing its contribution to the light background and also to limit the spread of atomic beam material in the apparatus. A
molybdenum oven has been machined to fit into and around a ceramic encapsulated tungsten heater. This results in good thermal contact, and optical coupling of the heater to the oven and exposes the coolest surface so that the light background is minimized. The oven opening of 50 mils serves as the first atomic beam defining slit. The oven, when operated at a maximum temperature of about 1400°C, contributes only a few hundred counts per second to the photomultiplier count rate.

The light scattering chamber optics is designed to collect about 12% of the scattered light. The light is collected in both a hemispherical mirror and a condensing lens system and is focused through a set of razor edge slits. Only light that originates in the cone angle of the mirror and the condensing lens should pass through the slit, so that the optical apparatus is in principle isolated from most background light. Since none of these components are perfect some background light enters the PMT, but with the inside of the chamber brightly lit by the ion pump injector filaments, the light baffle and optical elements limit the PMT count rate to about \(5 \times 10^5\) cps. Normally the injector filaments will be turned off. The background from laser light is very small. With a laser beam of a few tens of milliwatts (approx. \(10^{17}\) photon/sec) the PMT sees only a few thousand cps due to the laser beam.

2. **Dye Laser Stability**

The resolution of our system is limited by the bandwidth of the dye laser output. There are several possible sources of linewidth
broadening but we have determined that it is almost entirely due to mechanical vibrations of the laser cavity. This was demonstrated by setting the dye laser output wave length on the side of a Doppler-broadened iodine line and then observing the amplitude variations in the transmitted laser light (see Fig. 33-3). The crystal that drives the prism in the laser cavity provides a pick-up signal for vibrations in the cavity. Fig. 33-3 shows the high level of correlation that exists between the mechanical vibrations and the laser frequency jitter. An attempt was made to feed-back the amplified crystal output to the cavity mirror. This was successful initially in reducing the frequency jitter from about 40-50 MHz to about 17 MHz, but that was using a dye circulator not equipped with a vibration isolator. When used with a circulator that is so equipped, the stability of the system is about 15-18 MHz and is not improved by the feedback circuit. This is a result of the frequency response of the crystal-mirror combination used for the cavity translator.

The cavity length was then modulated by a sinusoidal voltage on the crystal and the frequency modulation measured using the iodine cell. The results presented in Fig. 33-3 show that the system has a significant phase lag for frequencies exceeding about 100 Hz. Since the major contribution to the FM jitter is at a few hundred Hz with the vibration isolator installed the feedback circuit does not help. A method of varying the optical path length in the cavity at higher frequencies would apparently substantially reduce the bandwidth of the laser. Such techniques are being investigated.
Using the output of the prism translating crystal is was found that the cooling water flow to the magnet and plasma tube of the argon ion laser was the dominant contributor to the FM noise of the dye laser. When the water flow through the laser was reduced the resolution of the system was substantially increased. Figure 33-4 compares the previous resolution with that currently being obtained. Additional measures to reduce vibration are planned and may eliminate the need for a servo control system.

3. The Wavemeter

The wavemeter provides an automatic readout of the tunable dye laser's wave length every two seconds with an error of about 0.25 Å. This is accomplished by comparing the accurately known wave length of the 5145 Å line of an argon ion laser with that of the tunable laser using a simple interferometer. The scheme is illustrated in Fig. 33-5.

As can be seen from the figure, part of the light from both the argon pump laser and the dye laser is split off and formed into a single beam which enters the interferometer though an optical isolator. (The isolator prevents any reflected light from re-entering the lasers and affecting their stabilities.) This beam is split into two paths, one of which is terminated with a stationary mirror and the other with a moving mirror driven by a Goodman Mossbauer vibrator. As the light from the two paths is recombined, the relative phase depends on the position of the moving mirror with respect to the fixed mirror. Consequently each time the vibrator moves the mirror one stroke either backward or forward, a series of nodes are detected by the photodiodes. The interference filter in front of PD5 transmits the longer wave length light from the tunable laser and reflects the 5145.32 Å light from the pump laser into PD6.
The output from each photodiode is amplified and sent to a discriminator which generates a logic pulse each time the signal crosses a preset threshold. Therefore two logic pulses are produced for each node in the signal. Another circuit, which senses the turning points in the vibrator's travel, inhibits the production of logic pulses while the mirror's motion is non-uniform and also sends out reset pulses to the scalers at the end points of the mirror travel. The ratio of the number of logic pulses from each circuit generated during one vibrator stroke is displayed automatically by an ITRON-650 counter. This ratio is the reciprocal of the ratio of the corresponding wave lengths. The wave lengths corresponding to these ratios have been tabulated.

The principal limitation on the wavemeter's accuracy is the number of nodes counted. For light from the argon pump laser, about 10,000 nodes (20,000 counts) can be recorded in one 5 mm sweep, yielding an accuracy of about $5 \times 10^{-5}$ which corresponds to about 0.25 Å. Jitter in the vibrator's motion would cause additional error, but the reproducibility of the measurements indicates that this is negligible. The overall accuracy was checked by using the interferometer to measure the wave length of 6328.20 Å light from a He-Ne laser relative to the light from the argon laser. The measurement yielded a value for the wave length correct within the expected error.
LASER LIGHT SCATTERING CHAMBER, ATOMIC BEAM OVEN AND LIGHT COLLECTION OPTICS
LASER LIGHT SCATTERING CHAMBER AND LASER BAFFLES
Fig. 33-3. Oscilloscope traces show the FM jitter of the dye laser (the trace with high frequency noise) and the output of a crystal in the laser cavity. The magnitude of the FM jitter is approximately 15 MHz RMS. This shows that the FM noise is almost entirely due to mechanical vibrations in the laser cavity. The lower photographs show the phase lag of the feedback signal at 100 hz and 400 hz.
Fig. 33-4. The improvement of resolution for the $^{170}$Yb and $^{173}$Yb(5/2) component of the 5556Å transition.
Isotope-Shift Wavemeter

B: Beam splitters with the percentage of reflected light indicated
M: Mirror
I: Interference filter
O-I: Optical isolator
PD: Photodiode
Development of techniques to measure the impact parameter dependence of inner shell vacancy production has continued. We have emphasized K-shell vacancy production by low energy protons in heavy elements. The objective of these measurements is to provide a more rigorous test of the currently available theoretical models for inner shell vacancy production. These are the Binary Encounter Approximation (BEA) as formulated by Garcia and Hansen and the Semi-Classical Approximation (SCA) of Bang and Hansteen and the more recent relativistic version of this model due to Amundsen and Kocbach. The Plane Wave Born Approximation has been widely used for comparisons with total cross section measurements but Born approximation angular distributions are not available.

Recently there have been many measurements of total X-ray cross sections for many targets, beam projectiles and energies, but data on the impact parameter dependence of the cross sections (angular distributions) are relatively rare. This is due to the experimental difficulties associated with the small excitation energies and small cross sections relative to the elastic scattering.

We have developed a technique which allows us to make measurements with good accuracy in a short period of time. 4 MeV protons are scattered by foil targets (\( \sim 50 \mu \text{g/cm}^2 \)) and enter the Enge
Split Pole Spectrometer (Fig. 34-1). The spectrometer has sufficient dispersion and resolution to focus and separate protons that have been elastically scattered and those that have inelastically scattered due to K-shell vacancy production. The physical separation is about 2 cms. An example of the focal plane spectrum obtained is shown in Fig. 34-2. This arrangement allows separate but simultaneous detection of elastics and inelastics. The elastics are detected by a plastic scintillator (NE 102) - photo multiplier combination which allows very high count rates ($10^5 - 10^6$ cps). The inelastically scattered particles were detected by a surface barrier detector and recorded in coincidence with target X-rays. The X-rays were detected by a 1/16" thick, 2" diameter NaI crystal placed less than an inch from the target beam spot. The coincidence yielded a time resolution of $\sim 6$ nsec and typical real-to-random ratios of 100:1. A typical TAC spectrum is shown in Fig. 34-3.

The separate detection of inelastics resulted in an improvement in the real-to-random ratio of a factor of about 200, due to the reduction of random coincidences from the elastics. Simultaneous measurement of elastics and coincidences minimized systematic errors due to beam spot movement and target non-uniformity. Data collection times ranged from 10 mins. to a few hours per angle. The angular range $2.3^\circ$ to $30^\circ$ was covered, corresponding to impact parameters between 600 and 60 fm.

The present arrangement gave accurate relative values for the X-ray differential cross sections. The data were normalized by measuring the total X-ray production cross section with a Si(Li) detector. The total cross section results are given in table 34-1.
along with the predictions of various models. The data for tantalum, gold, bismuth and uranium are shown in Fig. 34 -4 with the theoretical predictions of the BEA, SCA and relativistic SCA. The relativistic corrections are large and substantially reduce the discrepancy between theory and experiment. The fit of the RSCA to the shape of the distributions is excellent although the predicted total cross sections are consistently too large by about 15 - 20%.

The large relativistic effect is expected since the K-shell electrons are tightly bound and require a large momentum transfer for vacancy production. Because of the large mass difference between the electron and the proton, the vacancy production process is most probable for high momentum electrons; i.e., the most relativistic electrons. This shifts the peak production to small impact parameters (far inside the average K shell radius) where the electron kinetic energies are on the order of 1 MeV.

Our results support the view that the SCA with relativistic wave functions provide an adequate description of the process.

We have also been able to measure indirectly the energy distribution of the ejected electrons by using a position sensitive detector (PSD) instead of a surface barrier detector and gating the PSD spectrum with the TAC peak. Doing this, we obtain the spectrum shown in Fig. 34 -5. The energy distribution of the scattered protons reflects the energy distribution of the ejected electrons. The prediction of the DWBA for the electron energy distribution is also shown, although that calculation is integrated over all impact parameters.
Table 34-1. Total Cross Sections (mb)

<table>
<thead>
<tr>
<th>Element</th>
<th>Expt.</th>
<th>RSCA</th>
<th>SCA</th>
<th>BEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta(Z=73)</td>
<td>93.4 ± 5.0</td>
<td>109</td>
<td>49</td>
<td>71.4</td>
</tr>
<tr>
<td>Au(Z=79)</td>
<td>47.4 ± 2.4</td>
<td>57</td>
<td>17</td>
<td>30.4</td>
</tr>
<tr>
<td>Bi(Z=83)</td>
<td>31.1 ± 2.0</td>
<td>35</td>
<td>8</td>
<td>17.5</td>
</tr>
<tr>
<td>U(Z=92)</td>
<td>11.7 ± 0.7</td>
<td>14.4</td>
<td>—</td>
<td>5.1</td>
</tr>
</tbody>
</table>

References

Fig. 34-1. Split-Pole Spectrometer
Fig. 34-2. Spectrum in focal plane of protons elastically scattered from Au.
Fig. 34-3. Time-to-Amplitude Converter Spectrum of protons in coincidence with K X-rays.
Fig. 34-4. Impact parameter dependence of X-ray differential cross sections.
Fig. 34-5. Spectrum of protons in coincidence with K X-rays.
Further progress has been made on the previously reported study\(^1\) of L-subshell ionization cross sections for uranium by protons (2 - 18 MeV) and alpha particles (3 - 16 MeV). Fig. 35-1 shows the results of U L-subshell ionization cross sections, \(\sigma_{1,2,3}\), plotted as a function of projectile energy per atomic mass unit. The theoretical predictions of the plane wave Born approximation\(^2\) (PWBA, dashed curve), the semiclassical approximation\(^3\) (SCA, solid curve), and the binary encounter approximation\(^4\) (BEA, dashed-dotted curve) are also included for comparison. For L\(_2\) and L\(_3\) ionization cross sections, all three models are similar and fit the experimental data very well. However, the measured L\(_1\) subshell cross section shows a distinct change at \(~1.25\) MeV/amu which is well described by PWBA and SCA calculations, while the BEA fit is unsatisfactory. Since the 2s state differs from the 2p state by an extra node in the radial wave function and since the cross sections at low bombarding energy are expected to be approximately proportional to the square of the momentum wave function, the kink in the \(\sigma_1\) curve in Fig. 35-1 and the position of the minimum in the \(\sigma_1/\sigma_2\) ratio in Fig. 35-2, result from the extra node in the momentum distribution for the 2s state.

The energy dependence of the \(\sigma_3/\sigma_2\) ratio is shown in Fig. 35-3. The decrease of the \(\sigma_3/\sigma_2\) ratio for the low energy alpha particle
data is similar to those previously reported by Datz et al.$^5$ and Chang et al.$^6$ for low energy He ions on Au. This result supports the explanation based on the simultaneous multiple ionization effect proposed by Datz et al.$^5$ Data for $^{12}$C and $^{16}$O beams are being obtained to examine this effect.

References
Fig. 35-1

U L-Subshell Ionization Cross Section

$L_1$

$L_2$

$L_3$

$\sigma_{L_{1-3}} / Z^2$ (BARNs)

$E/M$ (MeV/amu)

- Protons on U
- Alphas on U
- SCA
- PWBA
- BEA
URANIUM (Z = 92)

\[ \frac{\sigma_1}{\sigma_2} \]

\[ E/M \ (\text{MeV/amu}) \]

- Protons on U
- Alphas on U

- SCA
- PWBA
- BEA
URANIUM (Z = 92)

$\frac{\sigma_3}{\sigma_2}$

- Protons on U
- Alphas on U
- SCA
- PWBA
- BEA

P5. 35-3

E/M (MeV/amu)
D. EXPERIMENTAL EQUIPMENT AND TECHNIQUES

36. Heavy Ion Particle Identification

J.F. Petersen

In order to measure a given heavy ion reaction, the outgoing particles of interest must be identified out of the large population of various ion species which are typically produced when a heavy ion beam is incident on a target. In particular, the mass \( A \) and atomic number \( Z \) must be determined. If a magnetic spectrometer is to be used to measure the particle energy \( E \), then \( q \), the ion charge, must also be found. In general, the determination of the four variables \( A, Z, E \) and \( q \) will require the measurement of four quantities. In practice, however, knowledge of the \( Q \) values for production of the different species often enables identifications to be made with only two or three measured quantities.

Much of the heavy ion data described elsewhere in this report were taken with an Enge split-pole spectrometer. In this work, two quantities, energy and position along the focal plane, were measured with Ortec solid-state position-sensitive detectors. Particle identification done these two signals is based on the following fact: for a given position along the focal plane, the energy \( E \) is proportional to the quantity \( q^2/A \). Note that \( Z \) is not in the expression, thus an \( ^{18}\text{O} \) \( 7^+ \) ion and an \( ^{18}\text{F} \) \( 7^+ \) ion with the same energy come to the same place on the focal plane. In most cases, however, for a given beam and target, there is an energy for every \( A \) above which only one \( Z \) is kinematically allowed. Another problem arises when the \( q^2/A \) is very similar for different values of \( q \) and \( A \). For example, \( q^2/A \) for
$^{14}_{\text{N}} 6^+$ is 2.57 while for $^{19}_{\text{F}} 7^+$ it is 2.58. Again, Q values restrictions often eliminate one of two closely spaced groups. Despite these limitations then, a complete determination of A, Z, q, and E for reactions of interest can often be made just using the two measured quantities described above.

In using this method with existing computer software, one complication arose. It was possible to sort the position output of a given detector into different position output of a given detector into different position spectra on the basis of the corresponding energy signal, i.e., to sort on $q^2/A$. However, the detectors have a finite length, 4.5 cm, which means that along a detector the energy of given species changes due to the dispersion of the spectrometer. In addition, nonlinearities in the response of the detector at the end regions gives a further spreading the energy signals for a given $q^2/A$ incident on the detector. As a result of these two effects and the finite energy resolution of the detector, the energy spectrum observed from a detector consists of broad overlapping peaks rather than narrow discrete spikes quantized as $q^2/A$. A typical spectrum taken with the old software is shown in the bottom half of Fig. 36 -1.

In order to improve the situation and thus facilitate better particle identification, the software was modified this last fall. The new version of the data collection program has the capability of "correcting" the raw energy signal. Instead of sorting with the energy signal, E, the quantity $E - C_1 \cdot XE - C_2 \cdot (XE)^2$ is used. XE is the position signal from the PSD (the position is determined by
digitally dividing $X E$ by $E$). The quantities $C_1$ and $C_2$ are constants which can be set externally to empirically give the best $q^2/A$ resolution. Note that the term $C_1 \cdot X E$ would be the only one necessary if the detector response was perfectly linear. An energy spectrum using the new software is shown in the top half of Fig. 36-1, with several of the particle groups identified. This top spectrum was generated from the same data (coincident raw signals stored on magnetic tape) as was used to produce the lower spectrum. The data were taken with a 50 MeV $^{18}$O beam incident on a $^{48}$Ca target. Although the extra computations in the new version slow down the data processing time slightly, this is not a problem with the low count rates found in heavy ion induced reactions.
Fig. 36-1. Heavy Ion Particle Identification
In order to determine absolute cross sections in the \((p, np)\) studies, we wished to obtain the neutron detection efficiency of the 5.08 cm x 5.08 cm (dia.) cylindrical NE 213 liquid scintillators used in the experiment. During the data-taking runs, the energy threshold (bias) was set at the midpoint of the \(^{22}\text{Na}\) 0.511 MeV gamma ray Compton edge (1.6 MeV neutrons, or 0.341 MeVee\(^*\)) and pulse shape discrimination was used to separate neutron events from gamma ray events. As is explained more fully later, it is difficult to calculate the neutron efficiency reliably, and eventually we decided to determine this quantity by transporting a scintillator, photomultiplier tube and base to Lawrence Livermore Laboratory (LLL) and directly comparing its count rate with that of previously calibrated LLL NE 213 detectors. The comparison was made at six neutron energies spanning the range observed in actual data-taking. For the comparison, all detectors had the energy bias set at 1.6 MeV (neutrons) and pulse shape discrimination was used. The average normalization ratio (Minn./LLL) was \(\bar{N} = 1.124 \pm 0.015\) (\(\sigma = 0.0068\)). It is surmised that \(\bar{N}\) differs from unity because the Minn. scintillators are contained in a brass can which may cause scattering in of neutrons. The LLL detectors were originally calibrated by a simple fit to measurements at

\*MeV-electron-equivalent: the electron energy needed to produce a pulse of height equal to that produced by a neutron of given energy.
several energies using the associated-particle technique and the reactions \(d + d \rightarrow {}^{3}\text{He} + n\) and \(d + t \rightarrow {}^{4}\alpha + n\). This fit to data is shown, for the energy region of interest, by the solid curve in Fig. 37-1.

During data-taking at Minnesota, the target-to-scintillator distance is normally 40 to 60 cm, whereas the LLL flight path is several meters. We have modified the detector calibration at LLL to account for the effect of finite detector thickness on solid angle, based on the following assumptions.

1. Scattering by carbon in the scintillator may be neglected.
2. Every n-p collision in the scintillator produces a proton recoil which is detected and no neutron is scattered twice.
3. The n-p scattering cross section is isotropic in the center-of-mass system (good for up to 14 MeV neutrons).
4. The energy dependence of the neutron detection efficiency is the same for any length flight path.

Using the first three assumptions, an expression was obtained which reproduced the curve \(\varepsilon_L\) which was found to fit measured values at LLL. The fourth assumption was then employed to obtain \(\varepsilon_M\), the neutron efficiency for short flight paths at Minnesota:

\[
\varepsilon_M = \frac{1 - \exp[-n_H\sigma_H LR_0/(R_0 + L)]}{1 - \exp[-n_H\sigma_H L]}
\]

where:

\(\varepsilon_L\) = efficiency measured at LLL (solid curve, Fig. 37-1).
\(n_H\) = hydrogen number density in the scintillator.
\( \sigma_H = n + H \) cross section,

\( L = \) scintillator thickness,

\( R_0 = \) flight path length.

The uncertainty in \( \epsilon_n \) is estimated to be \( \pm 7\% \).

Prior to the efficiency calibration of the scintillators, extensive efforts were made to calculate the detection efficiency, using a Monte Carlo program\(^2\) which does not make use of simplifying assumptions 1-3 above. That is, effects such as double scattering, scattering by carbon, proton escape and statistical fluctuations are taken into account.

The program was first tested by comparing its results to measured efficiencies\(^3,4\) for NE 213 scintillators of various geometries. Disagreement with these measured values led to an investigation of difficulties inherent in the use of the program. First, the calculation uses an expression\(^5\) for the light output from protons in scintillators with saturation properties considerably different from those of NE 213. Two different substitutions for the proton light output in NE 213 were examined: an empirical expression used by Batchelor, et al.\(^6\) and a table resulting from fits to measured values by Verbinski, et al.\(^4\). Some improvement in the agreement with measured efficiencies was noted using the latter substitution. However, the effect of scintillator saturation properties is masked, to a great extent, by an ambiguity in the program. Finite pulse height resolution in the scintillator is simulated by the choice of the "one photon electron level" (one p.e. level) i.e., the effective light energy needed to
produce one photoelectron in the photomultiplier. The "bias" in the program which reproduces the actual (experimental) neutron energy threshold is dependent on the choice of the one p.e. level. These two values are thus divorced from physically measured values and become, in essence, adjustable parameters. That is, there exists no a priori method of determining their dependence on scintillator properties and geometry.

The dashed curves in Fig. 37-1 indicate the effect of adjusting the bias and one p.e. level. All three curves were calculated using the Verbinski table for the proton light output in NE 213. As can be seen from curve 1, using the experimental value for the bias in the program results in a neutron energy threshold which is far too low. No combination of bias and one p.e. level would adequately reproduce the measured efficiency at all neutron energies, as is illustrated by curves 2 and 3. In addition, all the curves show structure between 4 and 6 MeV which is not found for the measured (solid) curve.

References

5. R. J. Kurz, A 709/7090 FORTRAN II Program to Compute the Neutron Detection Efficiency of Plastic Scintillator for Neutron Energies from 1 to 300 MeV, UCRL-11339, Lawrence Radiation Laboratory, Mar. 1964.

**NE213 NEUTRON DETECTION EFFICIENCY**

5.08 cm × 5.08 cm (DIA.) SCINTILLATOR

- **FIT TO MEASURED EFFICIENCIES,**  
  LAWRENCE LIVERMORE LABORATORY  
  BIAS = 0.34 MeVee

- **EFFICIENCY CALCULATED BY MONTE CARLO PROGRAM**
  1. BIAS = 0.34 MeVee  
     ONE P.E. LEVEL = 0.15 MeV
  2. BIAS = 0.56 MeVee  
     ONE P.E. LEVEL = 0.00 MeV
  3. BIAS = 0.56 MeVee  
     ONE P.E. LEVEL = 0.15 MeV

**Fig. 37-1**
During the year no major hardware changes have been made to the data acquisition system. At the end of 1974 the analog-to-digital converters were moved into bays connected to the signal ground of the experimental data acquisition equipment (amplifiers, discriminators etc.), and ground independent differential transmission to the computer data port established. This change has eliminated the slow drift previously produced by small unstable potential differences between the computer and signal grounds, and has enabled DC coupling to be employed through detector-amplifier chains. The increase in stability and therefore in apparent resolution has been especially helpful to the experimenter groups making scattering chamber measurements.

Re-programming of the 3100 system resident, necessary for implementation of the interfaced CDC 1604/CDC 3100 system, is essentially complete and initial testing of the new system is progressing. In addition, sequential access disk utility scratch files are also being incorporated into the new system to allow added convenience in manipulation of experimental data.

Improvements to of the system routines used in data acquisition have also been effected. The particle identification routines, INITIAlA and THRESH, have been expanded from four to seven particle thresholds. The 32-scaler routine, SD, has been modified to overflow after 16.7 million counts instead of 8.4 million as it did previously.
Control Data 1604

This machine is not in use at the present for data reduction. Its original role as extended memory for the CDC 3100 computer has been taken over by the fixed disk unit described previously, and it is therefore intended to develop routines for the 1604 computer to enable interactive data reduction to be performed.

The extensive software modifications to the CO-OP MONITOR operating system, used by the 1604 computer, necessary in conjunction with CDC 1604/CDC 3100 system are now nearly complete and preliminary testing is in progress. In these modifications the external user characteristics of the CO-OP MONITOR have been largely preserved to allow comparibility with established Control Data 1604 software.

A complete library of 1604 routines, no longer available from Control Data, has been obtained from the University of Minnesota computer center which formerly operated another 1604 installation.

This library contains Fortran 63, CODAP (1604 machine language assembler), ALGOL, and many mathematics and utility routines.

Control Data 160A Computer

A Control Data 160A computer with 8K of 12-bit words and buffered Input/Output has been obtained from excess property. This machine will be used as the controller unit in a medium-speed remote Input/Output terminal to the University of Minnesota Control Data Cyber-74 computer system. This terminal is a desirable addition since the laboratory facilities are somewhat remote from the University computer center and the transportation of data back and forth has presented problems and delays. The hardware necessary to interface the terminal with the telephone line to the computer center has been built, and
programming of the control software is progressing. Also included in this terminal at the present time are a CDC 405 card reader and a CDC 166 line printer.

**Digital Equipment Corp. PDP-8L Computer**

This machine, which was originally electrically interfaced with the Control Data 3100, has now been reworked to act as a stand alone station, to enable data acquisition independent of the main CDC 3100 equipment. To this end, a 40 Kbyte/Sec. magnetic tape unit, a storage C.R.T., and analog-digital conversion equipment are being added, the interfacing of which should be completed by the end of 1975. An option called a data break facility has also been purchased for Digital Equipment Corp. for the PDP-8L. This option provides buffered input/output for the PDP-8L. This will provide additional speed in real time collection and subsequent dumping of data to tape. The first use intended for this machine is with the group working on optical isotope shifts as described in section 33 of this report. The software development for this application is progressing and should also be complete by the end of 1975.

**Reference**

Sputter Source
Steven F. Heppelmann

The Extrion Negative Ion Sputter Source has been used regularly during the past year. In this source, 20 to 30 keV cesium atoms are accelerated onto various cone materials. Negative ions which are sputtered from the cone are extracted to be injected into the tandem.

One value of this source is the great variety of ions which can be produced. While the duoplasmatron can only make beams of particles which are found in suitable gaseous forms, the sputter source uses either gaseous or solid material to obtain a wider variety of possible ions. Other advantages of this source include a very high ratio of beam current produced to material consumed. This is important in accelerating rare and expensive isotopes. The sputter source also eliminates the need for day to day maintenance such as filament changes. This allows for continuous running up to fifteen days. In comparison, on an oxygen run, the duoplasmatron requires a filament change every day. Such a change necessitates shutting down the source, breaking vacuum, installing the new filament, and pumping out.

In the last year the principal use of this source has been the production of $^{16}_0$ ions. Typical runs were about 10 days with ample negative-ion currents of 1-3 $\mu$A injected into the tandem. On these runs, the source often worked so well that its operators would ignore it for rather long periods of time. Any problems which occurred with this source could generally be traced to such an extended period of neglect. For example, it is possible for the source high voltage
power supply to trip off from time to time. If this happens while
the sputter source is on, the cesium is no longer accelerated onto
the cone but drifts around in the source. If this condition is main-
tained for long, the insulators become coated with cesium and become
conductive. To fix this the entire source must be disassembled and
cleaned with water. This job can easily take up most of a day. In
general, this problem occurred only rarely, and experimenters using the
$^{16}_0$ beam were very satisfied.

The method of obtaining the $^{16}_0$ beam was to inject air onto a
titanium cone. The beams produced were sufficiently intense since
the melting of targets became the limiting factor in many experiments.

Injected carbon beams of the microamp order of intensity were
also used during the year. A solid carbon cone was used to produce
this beam.

Several experiments have been carried out using an $^{18}_0$ beam.
Work was done to determine the most conservative method of producing
$^{18}_0$ ions. Various methods were used to coat the inside of cones
with the gas. It was found, however, that a very dilute $^{18}_0$ gas
could be introduced into the source in small quantities, again using
a titanium cone, to produce a satisfactory and economical $^{18}_0$ beam.

If great care was taken in setting up the source, it appeared that 1
gram of $^{18}_0$ could provide 1 $\mu$A of beam for one or two months. This
approaches one tenth of one percent of the consumed $^{18}_0$ actually
becoming beam. We felt that this was adequate for now. If $^{17}_0$ is to
be run, it may be necessary to try to boost the figure since that gas
is more expensive. This will require further work.
Investigation into new methods for introducing elements to be sputtered are continuing. Machinable elements or machinable compounds of elements can be made directly into cones. Other elements and compounds can be ground into powder and pressed into the surface of lead cones. Boron and calcium are being investigated at this time by pressing their powder into lead. These cones have not yet been tested, however.

One complaint which has been made against this source in other laboratories is that the phase space of the beam it produces is large, and thus transmission through the accelerator is very poor. There are several places in our beam line before the point of injection into the accelerator where a beam can be restricted. The beam which we measure coming out of the source and to the point of injection has very good phase space properties. It seems likely, then, that beam line restrictions are eliminating all but a relatively small solid angle of the beam coming from the source. Our transmission through the accelerator is as good as with the duoplasmatron.

The source does require maintenance at around 15 day intervals. We have found that the first major component to wear out is the ionizer. A pit develops in the sintered tungsten plug. If the ionizer is not replaced at this time, the pit can erode into a hole. Neutral cesium would then come into the source at a rapid rate and a complete cleaning would be required. It is not known why the pit develops in the ionizer. At first we ran with only 300 V of suppression for backstreaming negative charge. We suspected that this was not enough so we increased it to 2000 V. This change made little difference in the wear of the ionizer.
Cesium consumption is quite low; the chamber holds about 15 grams. When an ionizer is replaced the cesium is poured out under an argon atmosphere and stored before the replacement is made. Some cesium is lost in this process, and for that reason it is difficult to measure the source consumption. A good guess might be about 3 days per gram.

Although the ionizer heater seems very dependable if the source is left running, it is also very fragile. Start ups and shut downs are quite hard on it, and the tungsten leads to it are easily broken. The heater tends to fuse to the ionizer and can easily be broken when the ionizer is changed. In many ways it is the biggest problem in the source. We have been looking into some other designs for these heaters.

Our overall reaction to this source is very favorable. The most serious problems have usually been operator caused. Unlike the duo-plasmatron, there are several mistakes in operation which, if made, are not easily reversible. As more people become acquainted with the source these problems are diminishing.

-40- Sub-Microsecond Beam Chopper

J. H. Broadhurst, J. S. Lilley and M. A. Franey

A simple, versatile, electrostatic beam deflector has been constructed, installed and operated, stably and effectively for periods of several days in an experiment. The plate driver uses standard electronic components. It is triggered with a 10V "square-wave" precision pulse generator and is capable of switching the beam at any frequency between about 2 MHz and D.C., with a pulse
width limited only by the rise or fall time of the pulse (see below).

The deflector itself consists of a pair of parallel 16" x 2" x 3/16" aluminum plates in the low-energy beam line near the E.S.A.G. lens. Its action produces a vertical shift in the beam focus at the entrance to the accelerator which is about 45" downstream. The plates are separated by 9/16" shielded insulators. Accurate alignment and support are provided by two circular aluminum disks whose radii match the inner radius of the beam pipe. The entire apparatus is thus easily removed simply by sliding the supports and attached plates out of the beam line. However, since no transmittable beam strikes the assembly, normal procedure is to leave it installed and ground both plates.

The plates are driven at 1 volt/ns by 2N3739 NPN silicon power transistors operated in the linear mode, to a maximum of 280 volts. A switchable inverter allows logic control by either a positive or negative 3 volt input pulse.

Section 21 contains a report on the use of the switcher to measure short-lived residual α activity. In that experiment, the beam fall time (fully on to fully off) was ~45 ns, with a slightly faster beam rise time. The beam was pulsed at ~1MC, 260 ns beam on and 700 ns beam off. Very clean spectra of a 110 ns decay were obtained by enabling the detectors 30 ns after the beam was "fully-off". In this way, cross sections of a few μb were easily measured.
(1) General

During the past year no major problems have arisen in the operation of the accelerator and its associated equipment. During the early part of 1975 it was necessary for financial reasons to restrict operation to 80% of the total time available. However a supplementary grant from the University enabled full time operation to be resumed by March of this year. During these periods of experimental inactivity, machine development was undertaken and improvements made in the accelerator equipment. The overall summary of the accelerator operation is detailed in the following table.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Percentage of Total Time</th>
<th>Percentage of time with vacations and intentional shut-downs excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Time available to experimenters</td>
<td>64</td>
<td>72</td>
</tr>
<tr>
<td>Voltage Conditioning</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Machine Development</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Routine Maintenance</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Repairs and other downtime</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 41-1. Breakdown of Machine time, September, 1975 to September, 1975.
(2) Accelerator equipment

During this year the experimental beam tubes installed in the fall of 1974 have unfortunately further deteriorated. It appears that, although the electron trapping and hence the maximum steady voltage gradient attainable with the electrode configuration employed is superior to the beam tube design originally used, the current design for unknown reasons will not withstand the transient overvoltages that occur during major tank and column sparks. Thus large amounts of energy are deposited in the tube during such sparks, and rapid deterioration and eventual shattering of a few sections takes place during each attempt to condition the accelerator to high terminal potentials. For this reason limits have been placed from time to time this year on the maximum terminal potential that should be employed. Towards the end of 1975 the current beam tubes are to be replaced by rebuilt tubes of electrode configuration similar to the original design. It is hoped that these tubes will not have this problem of rapid deterioration, though no correlation between construction details and resistance to damage has so far been found.

The charging belt for the accelerator was installed in July 1974 and since then to date a total of 6827 hours has been accumulated without problems. This belt is of the "brown" type and, unlike the experience of some other users, has given no problems of tracking along its length, while its abrasion resistance and consequent lower dust generating properties compared with a "black" belt has again been demonstrated. Explanation of the satisfactory performance of
this belt may lie in the much lower transient longitudinal potential stresses during machine sparks produced by a machine operating with Nitrogen plus Carbon dioxide insulation rather than Sulphur Hexafluoride. The transient stress during this year has been further reduced because, in order to reduce beam tube damage, the accelerator has been operated at the minimum insulating gas pressure and consistent with the required terminal potential drive motor cooling. As a further safeguard an upper limit of 50 p.p.m. water vapour in the insulating gas has been set, with no belt operation above this humidity level.
(1) Voltage grading resistors

The laboratory has now had two years' operating experience with a single accelerating tube length (72 sections) of metal glaze resistors. A description of these resistors and the method used to mount them in the accelerator column is contained in the Williams Laboratory Report for 1974\textsuperscript{1}.

In use, the radial gradient between adjacent resistors during sparking transients should be safely below the value needed to cause transient ionization at the resistor element-Epoxy interface. However it is difficult to make this calculation with precision as the nearest spark gaps are rather remote from the resistor sites and local inductance can produce a considerable enhancement of the transient field strengths. Fig. 42-1 shows the current resistance values of the present resistors after about 12,000 hours use compared with a similar, (though not the same) set on delivery from the manufacturer (Victoreen Co.). The manufacturer's tolerance relative to the nominal value is shown by the dotted lines, while the same tolerance spread relative to the average value of the used resistors is shown by the dashed lines. No failures have occurred in these resistors, though the contact between the resistors and their support in the original design was unsatisfactory in two or three examples. The original spring contact was therefore replaced with a pressure contact which has given no further problems.
As Fig. 42-1 shows, gradual reduction in the resistance value does take place, and also the spread of the resistance values increases with use. However the performance so obtained represents a considerable improvement over the original resistors installed in the machine, and so it is proposed to extend the use of these metal glaze resistors to the remainder of the machine in the near future.

Before further development is undertaken to reduce the transient radial voltage gradient in the vicinity of the resistors it is intended to age a representative sample of the resistors, under D.C. conditions, external to the machine so that their expected performance can be established.

(2) Beam tube decoupling

The damage sustained by the present beam tube during machine sparks is directly attributable to the localized dissipation of energy in one or more of the inter-electrode gaps. This implies that a discharge occurs internally in an inter-electrode gap before the gap is bypassed by discharges across the tube and column protective spark gaps. Once such a discharge in the accelerating tube is started, then the fall in potential across the gap will prevent the protective spark gaps from firing, and the resultant current flow will damage both the polished surface of the electrodes and the glass surface of the insulator.

If the accelerating tube is not directly connected to the column structure, then transfer of energy stored in the capacitances between the column and the wall and between the column and the accelerating tube will be much reduced. This isolation has been obtained in other accelerators by independently grading the accelerating tube, and the machine
column, either with two independent sets of resistors, or with two independent sets of corona gaps.

The disadvantage of this approach is that the hardware in the machine is greatly increased, and for the same charging current-terminal potential relationship the impedance of each accelerating electrode relative to its neighbours is also doubled. This increase of impedance is undesirable as it raises the sensitivity of the machine to loading by the accelerated beam. For these reasons a simpler decoupling system has been installed during the year, the connection between the accelerating tube and the column structure, formerly a spring, being replaced by a resistor-spring combination. As these resistors are not part of the grading chain, their values need not be precisely controlled and their value can be chosen to provide a negligible increase in the acceleration electrode impedance.

The actual resistors used were 20-inch lengths of automobile resistive ignition cable, attached to the tube by a short spring. The length and the spring structure were chosen so that the tube inter-electrode capacitance, the spring inductance, and the resistive lead formed an over damped circuit with a calculated rise time of greater than 10 microseconds (resistance values approximately $10^4$ ohms). This time constant provides integration of the column transients applied to the accelerating tube and during sparks limits the current flow between the two members. Some anxiety was felt over the durability of these resistive leads, but over several months of use no failures have occurred.
The effect of these resistors has been to reduce tube damaging discharges, as measured by gas bursts in the tube vacuum during sparks, from a vacuum disturbance for each spark to no vacuum disturbances observed for sparks occurring at terminal potentials below 8.0 M.V. At potentials above 8.0 M.V. gas bursts occur with a fraction of the sparks, the fraction increasing with increasing terminal potential. At present the reasons for the onset of vacuum disturbances is not clear, it is thought however to correspond to column-to-tank sparks originating at the dead sections away from the terminal.

(3) Inter-tube electron suppression

The presently installed accelerating tubes were designed to provide excellent electron trapping and therefore to exhibit minimal inter-tube coupling. This intent appears to be borne out by individual tube potential withholding tests made using the longitudinal partial shorting system installed last year. At all times so far examined, the maximum terminal potential obtainable has corresponded to the maximum voltage gradient attainable across the most damaged tube in the accelerator.

However, with the reinstallation of acceleration tubes having electrodes of the original design it is expected that inter-tube coupling, the "long tube effect", will again be troublesome. In an attempt to eliminate coupling between accelerating tubes caused by untrapped electrons and slow ions generated in the residual gas by beam interactions, a magnetic trap has been designed to be installed in the 17-inch long dead section between accelerating tubes. The
construction of this trap is shown in Fig. 42-2, the outside being the normal commercial dead section installed in an M.P. accelerator. The construction uses alcomax-V ring magnets magnetized across their diameter to provide a dipole field within their bore. The first two magnets in combination produce a sideways deflection in the accelerated beam which is then corrected by the second magnet pair so that the net beam angular and spatial displacement is zero. Electrons and other particles with similar rigidity are however displaced sideways sufficiently so as to contact the bore of the tube between the center two magnets and thus be eliminated. The field strengths chosen produce complete elimination of incoming particles with rigidity less than or equivalent to 4 MeV electrons, secondary electrons produced by the impact of primary particles in the tube being trapped by the same magnetic fields. In order to prevent the introduction of electrons into the accelerating tubes from collisions of primary particles with the blanking plates at the end of the suppression assembly, the complete magnet system is insulated from its surroundings and so can be biased to provide a retarding field for the secondary particles.

A single unit of this trap has been constructed and field mapping completed in order to ascertain the aberrations produced and thus the increase in phase space of the accelerated beam. These maps indicate that a negligible increase will be produced, but show that a positive lens will act on the accelerated particles in a plane orthogonal to the plane of displacement. Fortunately as the of displacement is not restricted, compensation can be obtained by
installing the electron trap between the first two accelerating tubes with its bending plane orthogonal to the others in the low energy end of the machine. (In the high energy end of the machine the lens effect is unimportant.)

Figure 43-3 shows the net effect of the compensated system on the beam optics of the low energy side of the accelerator. For simplicity a circular electrode configuration has been chosen for the profile calculations so that the difference between a cylindrically symmetrical system (right side) and the same system after the introduction of the traps (left side) can easily be seen. (Note that the right side of each printout represents the vertical beam profile, the left the horizontal profile.) The print-outs for the acceleration of protons at a terminal potential of 2 MV indicate that the small remaining astigmatism will not decrease the transmission of the machine significantly, while at higher terminal potential and with heavier ions the astigmatism introduced should be completely negligible.

To verify this prediction a further set of three traps has been constructed. It is proposed to install them into the low energy side of the machine during the life of the present tubes and to examine their optical properties before completing a further set for the high energy side of the accelerator.

References
1. Williams Laboratory Annual Report, 1974, p. 156 and Fig. 46-1.
2. ibid, p. 184.
Number of Resistor Assemblies

RESISTANCE IN MEGOHMS

-2%

+2%

Distribution of new resistor values

Distribution of resistor values after one year of operation

Fig. 42-1
FIG. 42.2. Magnet Assembly to go into Dead Section of Accelerating Tube

Standard H.V.E.C. dead section (M.P.)

Ceramic insulators

Additional pumping apertures

Beam Path

Blanking for unused part of tube aperture

Ground strap

Diametrically magnetized magnets
Fig. 42-3
43. LAMPF Users Group

I. High Resolution Spectrometer (HRS) Physics Program. (G. Kyle, D. Madland, D. Dehnhard, N. Hintz)

The Minnesota LAMPF Group has directed its main effort toward nuclear structure studies using medium energy protons (200 ≤ E ≤ 800 MeV) at the highest resolution facility at LAMPF, HRS. To date, the group is participating in three experiments and has collaborated with LASL in the formulation of two others. All five experiments have been approved by the LAMPF Program Advisory Committee (PAC).

These are:

#15 Elastic Scattering and Total Cross Sections on H, D, and He.

#109 The Study of Microscopic Structure of Collective Modes.

#139 Preliminary Elastic Proton Scattering Survey.


#183 Proton Scattering Survey on Heavy Deformed Nuclei (148,154Sm, 166Er, 176Yb, and 238U). Co-spokesman - N. Hintz and J. Spencer.*

Experiments 178 and 183 comprise a study of elastic and inelastic proton scattering by deformed nuclei. The motivation is to extract detailed information on transition densities to determine nuclear shapes and shape changes, on collective and single particle modes,

*LASL Staff Member, Assistant Group Leader, MP-10
and on giant resonance splitting due to nuclear deformation—all at ranges of momentum transfer and nuclear penetrability which have heretofore been unattainable at high resolution. Accordingly, new features of deformed nuclei are expected to emerge.

Experiment #139 (the first experiment to be run) is now scheduled to begin Jan. 1976, the major source of delay having been the preparation of the two $75^\circ$ dipole magnets. Beam Line C (which provides the dispersion matched beam to the HRS) is complete and is scheduled for beam tune runs beginning on 15 Sept. 1975. The Minnesota group's contribution to the preparation of the facility has been concentrated on the spectrometer dipoles and the beamline, as discussed in the next two sections.

II. Status of the HRS $75^\circ$ Dipoles (HS-BM-01 and HS-BM-02).

(D. Madland)

In the twelve months since the last report, it has been determined that the optimization of the dipole fields by $H_t$ windings is not sufficient to achieve the design resolution. While it is possible to achieve a few parts in $10^5$ for the average of 3 NMR scans at three different azimuths, this average does not represent the field behavior at other azimuths or for all azimuths, i.e., field integrals at fixed $R$ (see Fig. 42-1, curve a). The main sources of the difficulty were determined to be inhomogenities in the mechanical gap (machining errors) and the relative motion (as a function of field excitation) between the ten blocks of steel comprising the magnet. It was therefore decided to disassemble the magnets and hand grind the pole surfaces.
The status of the dipoles prior to the grinding operation can be summarized by the fact that the mechanical gaps varied by as much as 9.2 mils (HS-BM-02) and 12.9 mils (HS-BM-01) out of a design gap of 4000 mils, that is, mechanical homogeneity was good to approximately 2-3 parts in $10^3$.

The hand grinding operation on the two dipoles and subsequent reassembly is completed. Field mapping studies on HS-BM-02 (the first magnet that was ground) together with leg shimming optimizations have been performed with positive results. HS-BM-01 is presently being prepared for the identical set of field measurements. A discussion of the grinding operation follows.

Correlation of several magnetic field and mechanical contour maps, for each magnet, made possible the construction of polar grids, for each pole piece, on which the amount of steel to be removed was known. The grinding operation consisted in removing to as close a tolerance as possible, the specified amount of steel from a polar area element about the grid point in question and to do so in such fashion that neighboring area elements would blend continuously into one another. This was done for four pole pieces with a total area of $\approx 180$ ft$^2$.

For HS-BM-02 there were 585 polar area elements of approximate dimension 2" radial by 4" azimuthal. Upon completion and reassembly, a mechanical contour map indicated that the following improvements could be implemented for the grinding of the other dipole, HS-BM-01:

1) A slight azimuthal "sine wave" variation in the gap height, with wavelength $\approx 4''$, indicated that the polar area element
should be changed to ~2" radial by 2" azimuthal.

2) Results at innermost and outermost radii indicated that mechanical contour maps on HS-BM-01 should have a larger radial extent so that a better job could be done on "blending" the base take off amounts into the Rojowski edge profiles.

These adjustments were incorporated into the HS-BM-01 operation and gave 1290 polar area elements per pole to be ground. Another improvement in the HS-BM-01 grinding operation was the realization that if too much steel was removed from a given area element an integral compensation could be made by reducing the amount of steel to be removed from the azimuthally adjacent element by an amount equal to the depth of the error.

In order to convey and compare the mechanical results of the grinding operation itself we have (A) tabulated the distribution of the measured deviations from the desired values for the total grid and (B) calculated the departure from the desired mechanical line integrals, for fixed R, through the total azimuth.

A. Distribution of Deviations from Desired Values

Let $\Delta y$ represent the total deviation from the desired amount of removal (of the combined poles) at some arbitrary grid point. Then a table can be constructed showing the distribution of these deviations for 585 $(r,\theta)$ coordinate measurement points for HS-BM-02 and 1290 such points for HS-BM-01 (not area elements; only center points of area elements):
Table 43-1.

<table>
<thead>
<tr>
<th>Range</th>
<th>No. of Grid Points (HS-BM-02)</th>
<th>No. of Grid Points (HS-BM-01)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>\leq 0.05$ mil</td>
</tr>
<tr>
<td>$0.05$ mil $&lt;</td>
<td>\Delta y</td>
<td>\leq 0.1$ mil</td>
</tr>
<tr>
<td>$0.1$ mil $&lt;</td>
<td>\Delta y</td>
<td>\leq 0.2$ mil</td>
</tr>
<tr>
<td>$0.2$ mil $&lt;</td>
<td>\Delta y</td>
<td>\leq 0.5$ mil</td>
</tr>
<tr>
<td>$0.5$ mil $&lt;</td>
<td>\Delta y</td>
<td>\leq 1.0$ mil</td>
</tr>
<tr>
<td>$1.0$ mil $&lt;</td>
<td>\Delta y</td>
<td>\leq 1.5$ mil</td>
</tr>
</tbody>
</table>

585                           1290

Note: In order that these $\Delta y$'s represent deviations from the desired gap it must be assumed that the magnets can be reassembled to coincide precisely with their original mechanical configurations.

B. Departures from Desired Mechanical Line Integrals

The departure from the desired mechanical line integral is given by

$$J = \frac{\int [y(\text{actual}) - y(\text{desired})/y(\text{desired}) \, dz]}{\int dz}$$

for each $R$. The results for the two magnets are shown in Table 43-2. Two comments can be made. First, the average of the deviations for the second magnet to be ground (HS-BM-01) is a factor 4 less than the first magnet (HS-BM-02), that is, $\langle J \rangle$ (HS-BM-01) = $0.334 \times 10^{-5}$ and $\langle J \rangle$ (HS-BM-02) = $1.338 \times 10^{-5}$. Second, the peak-to-peak difference in $J$ values is a factor 1.8 improved between the two magnets, that is, $\Delta J$ (HS-BM-02) / $\Delta J$ (HS-BM-01) = 1.8.
Table 43-2

<table>
<thead>
<tr>
<th>R (Inch)</th>
<th>J x 10^5 (HS-BM-02)</th>
<th>J x 10^5 (HS-BM-01)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125.8</td>
<td>1.733</td>
<td>0.758</td>
</tr>
<tr>
<td>127.8</td>
<td>2.097</td>
<td>0.379</td>
</tr>
<tr>
<td>129.8</td>
<td>2.013</td>
<td>0.284</td>
</tr>
<tr>
<td>131.8</td>
<td>1.619</td>
<td>0.253</td>
</tr>
<tr>
<td>133.8</td>
<td>1.789</td>
<td>0.316</td>
</tr>
<tr>
<td>135.8</td>
<td>1.845</td>
<td>0.231</td>
</tr>
<tr>
<td>137.8</td>
<td>1.518</td>
<td>0.458</td>
</tr>
<tr>
<td>139.8</td>
<td>0.867</td>
<td>0.506</td>
</tr>
<tr>
<td>141.8</td>
<td>0.224</td>
<td>0.521</td>
</tr>
<tr>
<td>143.8</td>
<td>0.783</td>
<td>0.348</td>
</tr>
<tr>
<td>145.8</td>
<td>0.671</td>
<td>0.395</td>
</tr>
<tr>
<td>147.8</td>
<td>0.867</td>
<td>-0.253</td>
</tr>
<tr>
<td>149.8</td>
<td>1.370</td>
<td>0.348</td>
</tr>
</tbody>
</table>

Note: In order that the J values represent deviations from the desired field line integrals, it must be assumed that the magnets can be reassembled to coincide precisely with their original mechanical configurations.

At this time the following results have been achieved for HS-BM-02:

1) Field integrals at fixed radius (125" ≤ R ≤ 150") are constant to within ±1/10^4 for the homogeneous region of the magnet and for 4 kG ≤ R ≤ 14 kG. (see Fig. 43-1, curve b for 10 kG).

2) The addition of symmetric pair poleface shims, designed for the residual inhomogeneities at 14 kG, have improved the 14 kG field integrals to ±3/10^5. (see Fig. 43-1, curve C).

Remaining options to be tried (having ground the pole faces) are H_t windings and the multipole magnet positioned between the two 75° dipoles. The contributions to the field integrals from fringe fields at entrance and exit boundaries are to be adjusted by machining the nosepieces of the field clamps at these boundaries.
III. Beamline Tuning and Diagnostics. (G. Kyle)

The University of Minnesota group has been collaborating with LASL personnel in tuning Line C. Because the HRS is a dispersion matched system, the beamline must be tuned to the same order as the HRS if the design resolution $\Delta p/p \leq 5 \times 10^{-5}$ is to be achieved. The method used is experimental ray tracing. A system of antistripers is used to prepare an $H^-$ beam of very small phase space. An antistripper is a 1 mg/cm$^2$ carbon foil with a small round or slit-like hole. It strips all but a selected part of the beam. This beam enters Line C and is observed with a series of 20 beam scanners with a resolution $\approx 0.5$ mil. The beam scanner system and Line C were described in the 1974 Progress Report. The antistripper system consisting of 4 foils located at LAST01, LAST02, LXST01, and LXST02 and the early part of Line C are shown in Fig. 43-2.

During the fall of 1974 run cycle the HRS had several shifts of beam time. The beam was run through the line to the end of the twister section. The run permit system was debugged and the magnet setting procedures determined. Beam profiles were measured in Line C to determine the usefulness of the concept of experimental ray tracing. A sample beam profile is shown in Fig. 43-3. This scan was taken with LCSZ02 which is located before the quadrupole doublet. The beam would have the largest size at this point. The full width at half maximum was found to be about 25 mils (Fig. 43-3). This is already a useful size and can be improved by tuning the switchyard differently.

During the shutdown some new beam diagnostic devices were designed and constructed. The ISICS is a pair of multiwire proportional counters positioned at $90^\circ$ with respect to each other and
perpendicular to the beam. They can be pulled in and out of the beamline by a linear actuator. Some of these chambers have a position resolution of one, others of two mm. They are run in an integrating mode over up to 64 beam pulses and are read out by a multiplexer/analog-to-digital electronics. This system will be installed at three locations along the beam line to allow beam profiles to be measured for a wide range of beam currents.

Beam scanners were designed for the HRS scattering chamber. These have scanning capability in both x and y direction whereas the scanners in the beamline scan only one dimension. They can be mounted in the scattering chamber, such that they bracket the target, or in other configurations. They were designed to be useful not only for measuring beam profiles but also as anticoincidence counters in some experiments. Another pair of scanners will be used with the HRS time-of-flight system.

The taut wire system (TW) provides an on-line method to measure changes in the mechanical alignment of the beam line components. The system consists of a pair of wires strung under tension parallel to the beam line about two feet away from the beam. An RF signal is fed into the wires. Magnetic pickups are attached rigidly to the magnets and their x-y position relative to the wire can then be read out and compared with previous readings. The long term position accuracy of the sensors is about 2 mils. The x-y magnetic pickups are needed to measure angular and position alignment of a magnet. A total of 88 sensors are used for the beamline and spectrometer.

IV. Energetic Pion Channel Spectrometer (EPICS) Physics Program
(D. Madland)

EPICS is the LAMPF facility for high resolution nuclear structure studies using pions. The design parameters are energy resolution
\( \approx 60 \) keV, angular resolution \( \approx 10 \) mrad, beam intensity \( \approx 10^8 \) /sec, and energy range 100-300 MeV. First experiments are expected to start in the spring of 1976.

Two experiments on EPICS were proposed and approved (By the PAC committee) in 1975. They are:

1. **Inelastic Pion Scattering by \(^{148}\text{Sm}\) and \(^{152}\text{Sm}\).** Co-Spokesman: N. Ensslin (Univ. of Colorado), D. Madland (Univ. of Minnesota), and C. Morris (Univ. of Virginia).

2. **Inelastic Pion Scattering by \(^{24}\text{Mg}\) and \(^{25}\text{Mg}\).** Co-Spokesmen: C. Morris (Univ. of Virginia) and N. Ensslin (Univ. of Colorado).

The experiments comprise a study of elastic and inelastic pion scattering by deformed nuclei, as do experiments 178 and 183 for protons. The available pion beam intensities, however, limited the number of targets to be a subset of those chosen for the proton experiments.

The motivation for these experiments is based upon the following facts:

1. For pion-nucleon scattering, near the \((3,3)\) resonance, \(\sigma(p^+ + p) \gg \sigma(p^+ + n)\) and \(\sigma(p^- + n) \gg \sigma(p^- + p)\); 2. For pion-nucleus scattering near \((3,3)\) resonance the interaction is surface peaked and is strongly isospin dependent. The following possibilities therefore exist for pion-nucleus scattering at \(E \approx 20\) MeV: 1) Elastic scattering with \(\pi^+\) and \(\pi^-\) may determine the relative difference between neutron and proton matter distributions \(\rho_N, \rho_Z\) in terms of, say, rms radii; 2) Inelastic scattering with \(\pi^+\) and \(\pi^-\) may allow the separation of neutron and proton components to the transition strength.

In the particular case of a strongly deformed nucleus, such as \(^{152}\text{Sm}\), the interesting possibility exists for measuring deformation
parameters, $\beta_L^Z$ and $\beta_L^N$, of proton and neutron matter distributions, separately. Certainly, the extraction of deformation parameters, $\beta_L$ with the intrinsic ground state wave function in the rotational collective model. Nevertheless, differences in $\beta_L^Z$ and $\beta_L^N$ would indicate the proton and neutron density distributions are not the same. It should be mentioned that the majority of the work on nuclear density distributions has been on spherical nuclei with proton-neutron distribution differences described in terms of rms radii differences, and the results have been inconclusive. It could be that deformed regions provide a better testing ground in that an angular dependent density distribution may imply localization of part of the neutron excess. On the other hand, neutron and proton densities may have identical shapes as has often been stated. In either case, it is noteworthy that only the leading (spherical) term in the multipole expansion of an angular dependent density contributes to the rms radius. Thus, the elastic $\pi^\pm$ scattering has to be measured. The spherical nucleus $^{148}\text{Sm}$ has therefore been included in $^{224}$ to determine the correct spherical densities ($\rho_N$ and $\rho_Z$) in the $^{148}\text{Sm}$ pion-nucleus optical potential. A deformed version of this potential will then be used as the starting point in the analysis of the $^{152}\text{Sm}$ data. In the Mg isotopes (Experiment $^{232}$ one would expect $\beta_L^Z \simeq \beta_L^N$ for $^{24}\text{Mg}$ because $N = Z$, so that $\rho_Z \simeq \rho_N$. However, for excited bands in $^{25}\text{Mg}$ a dramatic change may occur. To the extent that an excited band is made up of different states of the motion of a deformed rotating core ($^{24}\text{Mg}$) coupled to a particle occupying a single Nilsson orbit, the inelastic transitions for $\pi^+$ and $\pi^-$ scattering may be very different in strength depending upon whether the Nilsson orbit is occupied by a proton or a neutron. For a more complicated
Nilsson configuration, the ratio of $n^+$ and $n^-$ cross sections and the shapes of the angular distributions may be compared to that of a "pure" configuration to unfold the neutron and proton contributions to the transition strength.
Exit Linac

LAST01 - select beam size

LAQT1-2-3

LAST02 - $R_{11}=R_{22}=R_{16}=0$; select angular divergence

LAQT4-5-6

LABM01

LABM02

LINE A

LINE X

LXBM01

LXBM02

LXQT1-2-3

LXST01 - near monochromatic waist of LXQT

$LXBM03$

$LXBM04$

$LXQD1-2$

LXST02 - achromatic waist of LXQD

LCSZ01 - beam scanner pair

LCBM01

LCBM02

LCBM03

LCSZ02

LINE B

LCQD1-2

LCSZ03

LINE C

Fig. 43-3. Beam profile measured with LCSZ02 for a small phase space beam.
## Laboratory Personnel

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- John H. Broadhurst
- Ronald E. Brown
- Dietrich Dehnhard
- John S. Lilley
- Carl H. Poppe
- John A. Becker

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- Marvin Cage
- David A. Lewis
- T. K. Li
- David Madland
- Hans-Peter Morsch
- Jay F. Petersen
- Vladimir Shkolnik

### Research Assistants
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- Michael Franey
- Philip M. Hegland
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Curtis Lehrke
George Potter III
James Pilgram
Victor John
James Turgeon 7
Ray Johnson 7
Victor Christianson 8

Others

Roberta Olson (Secretary)
Gordon Schissel (Principal Stores Clerk)

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2 Permanent address - Lockheed Palo Alto Research Laboratory
3 Stationed at Los Alamos Scientific Laboratory
4 Terminated Aug. 1975
5 Terminated Nov. 1974
6 Terminated Sept. 1974
7 Terminated June 1975
8 Retired Nov. 1974

45. Advance Degree Granted, Academic Year 1974-75

46. 

Reports and Publications

(a) Published Articles

"Study of the $\alpha + \alpha$ System below 15 MeV (c.m.)"
W. S. Chien and R. E. Brown

"One-Quasiparticle States in $^{163,165}$Ho observed in the $(^3\text{He},d)$ and $(\alpha,t)$ reactions"
D. A. Lewis, A. S. Brood, and W. S. Gray

"Assignment of $J^\pi = 6^+$ to Two States of $^{16}O$ Via the $^{12}C(\alpha,^8\text{Be})^8\text{Be}$ Reaction"
D. R. James, J. L. Artz, M. B. Greenfield and N. R. Fletcher

"Sub-Coulomb Neutron Transfers from $^{17}O$ onto $^{40}Ca, ^{44}Ca$ and $^{48}Ca$"
G. D. Jones, J. L. Durell, J. S. Lilley and W. R. Phillips

"Odd-Even Features in $^3\text{He} + ^3\text{H}$ Scattering"

"Proton Occupation Numbers for $^{44}Ca$"
D. Dehnhard and M. E. Cage

"Study of the $^{12}C, ^8\text{Be}$ (g.s.) Reaction and Four-Nucleon Transfer on $^{24}\text{Mg}$, H. Ho, W. Dunnweber, D. Dehnhard, K. Mudersbach and J. P. Wurm,

"Pion-Nucleus Total Cross Sections from 88 to 860 MeV"

"High Resolution Measurements of Isotope Shifts and Hyperfine Splittings for Ytterbium using a cw Tunable Laser"

"Experimental Search for a Low-Mass Scalar Boson"
D. Kohler, B. A. Watson, and J. A. Becker

"Are Complex Form Factors Important in Microscopic Descriptions of Inelastic $^3\text{He}$ and $\alpha$ Scattering?"
H. P. Morsch
"Shell Effects in Collective Excitations and a Shell Model Description Using a Renormalized Effective Interaction"
H. P. Morsch

"Proton Decay of Excited Analog States Formed in $^{119}\text{Sn}(p,n)^{119}\text{Sb}(\text{IAS})$"
D. H. Fitzgerald and J. S. Lilley

"Anomalous Behavior of the (p,n)-Analog Reaction on the Molybdenum Isotopes"
C. H. Poppe, S. M. Grimes, J. D. Anderson, J. C. Davis, W. H. Dunlop, and C. Wong

"Energy Dependence of the (p,n) Analog Cross Sections of the Molybdenum Isotopes Between 16 and 26 MeV"
S. M. Grimes, C. H. Poppe, J. D. Anderson, J. C. Davis, W. H. Dunlop, and C. Wong

"Population of Analogs of Excited States in $^{63}\text{Cu}(p,n)$ at 16, 19 and 22 MeV"

"Study of $^{20}\text{Ne}(p,t)^{18}\text{Ne}$ Transitions with the Coupled-Channel Born Approximation"
D. K. Olsen, T. Udagawa, and R. E. Brown

"Proton-hole States Observed in the $^{166}\text{Er}(d,^3\text{He})^{165}\text{Ho}$ Reaction at 34.5 MeV"
D. A. Lewis and W. S. Gray

"A Test of the Core Excitation Model by the $^{107,109}\text{Ag and 106,108 Pd (p,t) Reactions}"
A. Kuhfeld and N. Hintz

"Equilibrium Charge State Distributions For $^{16}$O Ions At 20-65 MeV"
D. J. Weber, N. M. Hintz, and D. Dehnhard

"Three-Body Breakup Reaction $^{40}\text{Ca} (16_0, 12_0\alpha)$"
D. C. Slater, J. R. Hall, J. R. Calarco, B. A. Watson, and J. A. Becker
"Strong Polarization of the lp-Shell Core in the Lowest 0+ States of 24Mg and 28Si"
H. P. Morsch, D. Dehnhard, and T. K. Li

"Proton Decay of Analog States Formed in 119Sn(p,n)119Sb"
D. H. Fitzgerald G. W. Greenlees, J. S. Lilley, J. M. Moss and T. Woods

"Features of Inelastic Transitions and the Excitation of a Giant Monopole Resonance"
H. P. Morsch

"Machining Hyperbolic Electrodes with a Straight Edged Tool"
J. M. Blair

(b) Articles in Press or Submitted for Publication

"Be Producing Reactions in 12C + 12C, 16O + 16O, and 28Si + 12C"
J. L. Artz, M. B. Greenfield, and N. R. Fletcher
Phys. Rev. C.

"Study of the 29,30Si(16O, 15N) Proton Stripping Reaction at 60 MeV"
D. Dehnhard, J. L. Artz, V. Shkolnik and R. M. DeVries
Phys. Rev. C.

"Excited Analogs in 62Ni and 63Cu(p,n) and the Weak Coupling Model"
Phys. Rev. C.

"The (3He,n) Reaction in the Lower (2s1d) Shell"
J. F. Petersen
Nucl. Phys.

"Single Proton Transfer to 29,30P States"
W. W. Dykoski and D. Dehnhard
Phys. Rev.

"Relativistic Effects in the Impact Parameter Dependence of K-Shell Ionization of Heavy Elements"
D. L. Clark, G. W. Greenlees, J. H. Broadhurst, M. E. Cage, and T. K. Li
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