The research described above, contained in this report was performed at the Nuclear Physics Laboratory at the University of Washington during the year ending April 30, 1973. It was supported by grants from the United States Office of Science and Education, by the staff of the Laboratory, and by other groups from within and outside the University community.

The principal equipment of the Laboratory was a two-stage gas-filled Van de Graaff accelerator, constructed by the High Voltage Engineering Company and completed in 1949, and a conventional cyclotron -- the "Sixty-Inch" -- constructed by Laboratory personnel, and completed in 1952. The three-stage Van de Graaff accelerator produces a direct current beam of protons with energies controllable between 50 and 600 MeV. The 60-inch cyclotron, with energies available between 20 and 500 MeV, produces proton beams in the range 5 MeV (for deuterons, alpha particles, and heavy ions). Recent improvements at the laboratory have made it possible to vary the energy available for each of the beams in the range 1 to 5 MeV.

ANNUAL REPORT

Nuclear Physics Laboratory
University of Washington
June, 1973
THE COVER DESIGN

For our cover picture we continue the tradition of the past several years and show the photograph of the high pressure gas cylinders which store the nitrogen and carbon dioxide mixture used for insulating the high potential terminals of the two Van de Graaff machines. They form a group of towers which front on the Van de Graaff building and have aroused considerable local interest and curiosity.
INTRODUCTION

The research and technical work described in this report was performed at the Nuclear Physics Laboratory of the University of Washington during the year ending April 15, 1973. It was directed and executed by faculty and graduate students from the Departments of Physics and Chemistry, by the staff of the Laboratory, and by visitor groups from both within and outside the University community.

The principal facilities of the Laboratory are a three-stage Model-FN tandem Van de Graaff accelerator, constructed by the High Voltage Engineering Company and completed in 1967, and a conventional cyclotron -- the "Sixty-Inch" -- constructed by Laboratory personnel, and completed in 1952. The three-stage Van de Graaff accelerator produces a direct current beam of protons with energies variable up to 24.6 MeV. It is also used for deuteron, alpha particle, and heavy ion acceleration. Of the latter, the most popular projectiles have been oxygen and carbon ions. The cyclotron accelerates protons, deuterons, and alpha particles to essentially fixed energies of 11, 21, and 42 MeV, respectively.

Financial support for the Laboratory and for operations conducted with the Van de Graaff accelerator is provided by the Atomic Energy Commission under Contract A.T.(45-1)-1388, Program "A", and the State of Washington. Cyclotron operations are supported by State funds and by financial assistance from outside user groups. The major portion of the cyclotron time is now devoted to projects in nuclear medicine, which are outlined in Section 16. A National Science Foundation grant provided funds for the purchase of the Van de Graaff accelerator, a portion of the associated equipment, and approximately one half the construction costs of the laboratory building. The remainder of the building funds came from state sources. The State also provided considerable financial assistance for the initial construction of the cyclotron and building facilities.

The research in the Laboratory supported by the contract with the Atomic Energy Commission involves a wide range of current problems in nuclear physics. Within the limitations imposed by facilities and time, we encourage individuals and groups to pursue any avenue of research appropriate to the facilities we have available.

During the past year two recently operational experimental facilities, the University of British Columbia large NaI crystal spectrometer and the Lamb-shift polarized ion source, have found much application. The former has been particularly useful for the study of capture gamma rays with energy greater than 10 MeV, as is attested by a variety of experiments reported in Section 12 (for the most part, collaborations between University of British Columbia and University of Washington personnel). The polarized ion source has been used not only to elucidate isobaric analog resonances and inelastic proton scattering from nuclei (Section 10) but also has made it possible to prepare a polarized sample of excited $^{19}$F nuclei, necessary in the experimental search for parity violations in the gamma decay of such nuclei (Section 8).

Among the many other projects in the Laboratory we here call attention to
the following: Observation has been made of the gamma branch in the decay of the 238U shape isomer; the observed lines have been interpreted to mean that the excitation energy of the shape isomer is 2,559 MeV. A remeasurement of the branching ratio, $I_{\beta^+}/I_{\beta^-}$, for the 7.65-MeV state of $^{12}$C yields a value significantly higher than the currently accepted value; this new value implies that the rate of the stellar triple-alpha process ($3\alpha \rightarrow ^{12}$C) at a given temperature and alpha particle density is about 50% faster than previously thought. "Quasimolecular" sub-Coulomb resonances observed in $^{12}$C - $^{12}$C elastic scattering over a decade ago are now found to resonate also in the $^6$Be - $^{16}$O final channel; for the resonance near 6.0 MeV the preferred angular momentum assignment is $\Lambda = 4$ and the reduced width is intermediate in strength between that of the carbon elastic channel and the strongest other channel, thus supporting the interpretation that the resonant state involves an $\alpha$-cluster configuration.

Two of the most interesting experiments in the Laboratory have not yet yielded definitive results. One, already alluded to, is the search for parity violation in the gamma decay of the first excited state of $^{19}$F. The second concerns transitions between the rotational levels of a shape isomer; here, the desired conversion electrons coincident with delayed fission have been observed but the number of electrons corresponding to distinct transitions is still quite small.

Again, we include separate sections on "Medium Energy Physics" (Section 15), devoted to the plans of the LAMPF Users Group to measure total pion nucleus cross sections, and "Atomic Physics" (Section 14), which deals mainly with measurements of Auger electrons and x-rays following high energy ion-atom collisions.

Each individual report is intended to describe the status of experiments or developments which often are incomplete. The appearance of specific numerical results and conclusions here does not constitute publication, and should not be quoted without permission of the investigators. Although many experiments are continuations of work described in previous years, an effort has been made to insure that enough background material is included so that the raison d'être of the work is clear to the reader. All names are listed in alphabetical order but, where appropriate, we have underlined the person primarily responsible for preparation of the report.

Again this year, the last portion of this report, Section 16, contains brief descriptions of a wide variety of research projects conducted at the Sixty-Inch Cyclotron by groups from outside the Laboratory. These visitor groups, which come from other organizations within the University, from other universities and colleges, and from industrial organizations, have provided the material contained in this section, and we appreciate their contributions. Because of the obvious benefits of this work both to the Laboratory, and to the scientific community in general, such groups will continue to be welcomed here to the fullest extent possible within the limitations of time, maintenance, and safety.
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1. ACCELERATOR DEVELOPMENT

1.1. Van de Graaff Accelerator Operations and Improvements

Staff

Statistics of Van de Graaff accelerator operations are given in Table 1.1-1. Major improvements to the accelerator and associated equipment include the modifications to the terminal ripple remover described in Sec. 1.2 of this report, and the installation of the fast periodic polarization flip system on the polarized ion source described in Sec. 2.2. Other improvements include the following:

a) A remote drive and readout for the foil stripper was completed.

b) The nitrogen scavenging system was modified so that gaseous nitrogen can be scavenged directly from the main liquid nitrogen storage tank.

c) A Faraday cup was installed in the negative ion source box to aid in tuning the injector, the polarized ion source and the direct extraction ion source.

d) The diffusion pump on the spectrograph scattering chamber was replaced and a liquid nitrogen cooled baffle and valve were added. A momentary power failure protection circuit was incorporated in this system.

e) A butterfly valve was added, and the roughing lines and control system on the 24 in. chamber were modified to minimize oil backstreaming.

f) Several improvements were made to the polarized ion source in addition to those described in Sec. 2.2. The support structure for the Wien filter was redesigned to permit easier cleaning of the argon region. The expansion cup on the duoplasmatron was changed to a 60 deg. cone, and the mounting hardware changed to permit easier removal of the cup and aperture plate, and the acceleration voltage supply on the source was replaced with a more stable supply.
Table 1.1-1. Statistics of Van de Graaff Operation from April 16, 1972 to April 15, 1973

1. Division of time among activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operation a)</td>
<td>7543</td>
<td>86</td>
</tr>
<tr>
<td>Scheduled maintenance</td>
<td>479</td>
<td>5</td>
</tr>
<tr>
<td>Unscheduled maintenance</td>
<td>258</td>
<td>3</td>
</tr>
<tr>
<td>Unrequested time</td>
<td>490</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total b)</strong></td>
<td><strong>8760</strong></td>
<td><strong>100</strong></td>
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</table>

2. Division of beam-on time among particles

a. Two-stage operation

<table>
<thead>
<tr>
<th>Particle</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>1766</td>
<td>29</td>
</tr>
<tr>
<td>polarized protons</td>
<td>428</td>
<td>7</td>
</tr>
<tr>
<td>deuterons</td>
<td>328</td>
<td>6</td>
</tr>
<tr>
<td>$^3$He</td>
<td>313</td>
<td>3</td>
</tr>
<tr>
<td>$^4$He</td>
<td>1125</td>
<td>20</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>269</td>
<td>5</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>252</td>
<td>4</td>
</tr>
<tr>
<td>$^6$Li</td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>328</td>
<td>5</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>85</td>
<td>1</td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>8</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4895</strong></td>
<td><strong>81</strong></td>
</tr>
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</table>

b. Three-stage operation

<table>
<thead>
<tr>
<th>Particle</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>226</td>
<td>5</td>
</tr>
<tr>
<td>deuterons</td>
<td>854</td>
<td>14</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1120</strong></td>
<td><strong>19</strong></td>
</tr>
</tbody>
</table>

**TOTAL BEAM TIME** 6016 100

---

a) Includes all time the accelerator was under the control of an experimenter.
b) This is the number of hours in one year.

1.2 Terminal Ripple Remover

H. Fauska, G.W. Roth, K.A. Snoover, and W.G. Weitkamp

A beam energy regulator, the so-called Terminal Ripple Remover (TRR), installed on the tandem accelerator, was tested in prototype form last year. Initial operation was very encouraging, but problems remained. This year a new unit with modifications in circuitry and improvements in construction has been installed and operated successfully.
A block diagram of the entire regulator system is shown in Fig. 1.2-1. The regulator senses beam energy shifts by the usual method: the beam is magnetically analyzed and a signal is derived from the difference in current hitting the two edges of a slit. This signal drives a light emitting diode at the end of the accelerator tank. The light beam from the diode, modulated with the slit difference signal, is transmitted by lenses to the accelerator terminal. There it is detected, amplified, and applied to the beam stripper with the correct phase to counteract fluctuations in the terminal voltage.

The prototype TRR had several difficulties. First, with only the gas stripper insulated from the terminal, the TRR could not be operated with the more commonly used foil stripper. The new unit applies the correction signal to both the foil and gas strippers, allowing the regulator to be used during all accelerator operations, including heavy ion and three stage operation.

Second, it was difficult to adjust the prototype unit since no output metering had been provided. The new unit has a light-emitting diode and a second lens set to transmit to ground a modulated light beam with intensity proportional to the signal actually applied to the stripper. This readout simplifies adjustment of the regulator, and helps in trouble shooting the device.

Fig. 1.2-1. Schematic diagram of the terminal ripple remover and corona regulator.
Finally, tank sparks occasionally caused the light-sensitive transistor in the terminal to burn out. Protective diodes, inductances in the wiring, and more compact construction have essentially eliminated this problem. A schematic of the unit at the terminal is shown in Fig. 1.2-2. This unit has been operating continuously for about 8 months at terminal voltages up to 9 MV with no failures.

Misalignment of the lenses and belt dust coating the lenses have not caused anticipated problems because the light emitting diode used is capable of producing about 10 times as much light as is usually necessary to operate the TRR. Reductions in light intensity are easily compensated for by increasing the output of the diode driver.

The value of the TRR in improving accelerator performance has been most dramatically demonstrated in the increased transmission of the beam through the 90 deg. analyzing magnet, and in the greatly reduced intensity modulation and position fluctuation of the beam on target. At terminal voltages below 2 MV, where the accelerator is relatively unstable, improvements in transmission of as much as a factor of 5 have been seen. The improved transmission and position stability are particularly advantageous when tuning up very weak beams.

Because the regulator counteracts terminal voltage fluctuations, which are a major source of beam energy spread, the TRR should also decrease the energy spread in the beam. We have attempted to measure this decrease by observing the difference in the shape of a narrow resonance with the TRR on and off. For this purpose we would ideally like to use isolated resonances with known total widths which are small compared to the expected spread in beam energy. These resonances should also be excited strongly enough to be located easily and the shapes measured quickly. These resonances should also occur at a variety of beam energies easily reached by the accelerator.

The well known narrow resonance in $^{12}$C(p,$\alpha$)$^{10}$N at a proton energy of 14.23 MeV has been investigated for this purpose. The total width of this resonance is known to be $820 \pm 200$ eV. However, Dzubay et al. have estimated that the broadening of this resonance caused by thermal motion of the nuclei in the target should be between 700 and 1000 eV at normal temperatures. We have measured the shape of this resonance using a thick target, both with the TRR on and off. We see a difference only when the performance of the corona regulator is degraded by opening the image slit of the analyzing magnet to an unreasonably large value of 80 mils or greater. With reasonable slit openings (object plus image opening $\leq 50$ mils) we observe a width of approximately 1.4 keV, which includes both the effects of the natural width and the beam energy spread. Measurements are planned using a cooled target to see if beam energy spread can be determined accurately with this resonance.

A second resonance we have used is in $^{54}$Fe(p,p)$^{54}$Fe at $E_p = 3.229$ MeV. This resonance, as well as the resonance in $^{12}$C(p,$\gamma$)$^{13}$N, was used by Dzubay et al. to examine the performance of the TUNL accelerator. This resonance is sufficiently narrow ($\Gamma = 250$ eV) and at an energy where thermal broadening is sufficiently small (about 170 eV) that the observed shape should give an adequate measure of the beam energy spread. It is, however, at a low proton energy where the performance of the accelerator is not optimal, so the results of the measurement may not be typical of other, higher energies.
Fig. 1.2-2. Circuit diagram for the terminal ripple remover electronics installed in the terminal.
The measured line shape for the 3.229 MeV resonance is seen in Fig.1.2-3, as measured with the TRR on and off. The line shape measured at TUNL, which was measured with a quoted beam energy spread of 625 eV FWHM, is also given in Fig. 1.2-3. (Both the energy scale and normalization of our data have been adjusted to facilitate comparison of line shapes.) Although there are some differences in line shape between our measurement and the TUNL measurement, it is clear that the widths are comparable when the TRR is on, and that the width increases by 10 to 20% when the TRR is off. These measurements were made with the image and object slits set at 30 mils total opening each; with these settings the analyzing magnet would transmit a beam with a triangular energy distribution with a width of 1.2 keV FWHM if there were no regulation at all.

The resonance in $^{54}$Fe(p,p)$^{54}$Fe was also used to measure the effect of oscillation in the TRR. The TRR oscillates at a frequency of 1 kHz if the gain of the amplifier driving the light emitting diode is too high. With the regulator deliberately made to oscillate, a line shape very similar to the "regulator not operating" shape in Fig. 1.2-3 results. This suggests that care must be taken when setting up the regulator to insure that oscillation does not occur.

Work is presently underway to analyze the measured resonance line shapes more precisely, in order to obtain quantitative information on the residual beam energy spread when the TRR is operating.


1.3 Cyclotron Operations and Improvements

Staff

Statistics of cyclotron operations for the year ending April 15, 1973 are given in Table 1.3-1. This is the first year in the 22 years the cyclotron has
been operated that nuclear physics research is not the largest user of cyclotron time. Over the past several years nuclear physics research has been supplanted by a diverse group of outside users, mostly working in medical or reactor engineering fields. Brief reports of the specific projects undertaken by the outside users groups are given in Sec. 16 of this report.

Efforts at improving the cyclotron have centered around accommodating the fast neutron cancer therapy facility, and increasing cyclotron reliability. Among other projects, the water cooling manifold has been moved and partially rebuilt to make room for the therapy collimator, and the focus magnet power supply and regulator have been rebuilt to handle the higher current required to bring the beam to the therapy target.
Table 1.3-1. Statistics of Cyclotron Operations from April 16, 1972 to April 15, 1973

1. Division of time among activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
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<tr>
<td>Normal operation a)</td>
<td>2382</td>
<td>54</td>
</tr>
<tr>
<td>Scheduled maintenance</td>
<td>226</td>
<td>5</td>
</tr>
<tr>
<td>Unscheduled maintenance</td>
<td>151</td>
<td>3</td>
</tr>
<tr>
<td>Unrequested time</td>
<td>1661</td>
<td>38</td>
</tr>
<tr>
<td><strong>Total b)</strong></td>
<td><strong>4420</strong></td>
<td><strong>100</strong></td>
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2. Division of time among particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha particles</td>
<td>598</td>
<td>61</td>
</tr>
<tr>
<td>Deuterons</td>
<td>349</td>
<td>36</td>
</tr>
<tr>
<td>Protons</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>977</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

3. Division of normal operation time among users

<table>
<thead>
<tr>
<th>User</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Washington Department of Radiology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast Neutron Therapy</td>
<td>1134</td>
<td>48</td>
</tr>
<tr>
<td>Fast Neutron Activation Analysis of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td>642</td>
<td>27</td>
</tr>
<tr>
<td>18F Production</td>
<td>117</td>
<td>5</td>
</tr>
<tr>
<td>15N Ammonia Production</td>
<td>76</td>
<td>3</td>
</tr>
<tr>
<td>University of Washington Nuclear Physics Laboratory</td>
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<td></td>
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<tr>
<td>Atomics International</td>
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<td>12</td>
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<tr>
<td>University of Washington Department of Physics</td>
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<tr>
<td>Western Washington State College</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>University of Washington Department of Nuclear Engineering</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2382</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

a) Includes all time the accelerator was under control of an experimenter.
b) This is the number of hours in 52 5-day weeks of 17 hours per day.
2. ION SOURCE DEVELOPMENT

2.1 Terminal Ion Source

G. Roth and Staff

Last year a project to build and install a direct extraction negative ion source in the Van de Graaff injector terminal was begun. During this past year a major effort has been devoted to the construction and testing of the various components: a) the vacuum system, b) the direct extraction duoplasmatron, c) the power supplies and d) the readout and control systems. All of these components are completed or nearing completion and have been tested individually. The next major effort will be to assemble these components, along with various peripheral equipment, on to the wooden terminal mockup and complete testing procedures on the entire source assembly.

The overall design must meet four criteria, a) minimum weight, b) minimum volume, c) minimum power consumption, and therefore low heat dissipation, and d) maximum reliability. These criteria are the basis for a number of unique design features.

Vacuum System

The basis of the source vacuum system is a 500 l/s triode ion pump housed in a stainless steel enclosure which must withstand the accelerator tank pressure externally. A substantial design effort was made to minimize wall thickness and therefore weight of this vessel while maintaining a suitable safety factor against collapse. Both calculations and comparison of published data on collapse of test vessels were used in determining a wall thickness of 1/4". The collapse pressure should be 650 psi ± 50 psi giving a safety factor of 3 and a weight of 130 lbs. Stainless steel was chosen over aluminum primarily because of resistance to softening under elevated temperatures. Thus welding and bakeout can be done without altering strength limits.

The vessel has been fabricated, glass bead sand blasted, and pressure and vacuum tested. The glass bead sand blasting produces smooth clean interior surfaces. The pump, which has been extensively tested in a vacuum chamber, is now installed and operating in the pressure vessel.

Duoplasmatron

The ion source consists of a direct extraction duoplasmatron, an Einzel lens and a 5° bending magnet. This system will inject beam directly into the accelerator beam tube. The 5° magnet suppresses electrons from the source and rejects the rather large hydrogen beam present when the source is running on heavy ions. This is necessary to reduce beam tube loading.

The duoplasmatron uses a permanent magnet to produce the plasma constriction field. There will be no adjustment available for this field, but tests with an electromagnet showed that adjusting this field changed the source output by 10% at most. The permanent magnet is set to maximize beams of heavier ions.
since the hydrogen beam is larger than necessary. Use of a permanent magnet eliminates one power supply and reduces the heating of the source as well as exposing the arc chamber to air. This makes it possible to air cool the ion source, eliminating the need for a liquid cooling system in the terminal.

A prototype source has been constructed and operated for about 1500 hours on a test stand. The air cooled source will operate at atmospheric pressure with a small fan. Table 2.1-1 shows the type and intensity of beams that have been obtained. In all cases a mixture of about 3% of the desired gas in hydrogen was used. A higher ratio of heavy element gases caused the arc to be unstable and shortened the life of the filament.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Beam (ua)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁻</td>
<td>20</td>
</tr>
<tr>
<td>D⁻</td>
<td>20</td>
</tr>
<tr>
<td>C⁻</td>
<td>.050</td>
</tr>
<tr>
<td>N⁻</td>
<td>.06</td>
</tr>
<tr>
<td>OH⁻</td>
<td>10</td>
</tr>
<tr>
<td>CN⁻</td>
<td>10</td>
</tr>
<tr>
<td>C₂⁻</td>
<td>1.1</td>
</tr>
<tr>
<td>F⁻</td>
<td>12</td>
</tr>
<tr>
<td>N₂⁻</td>
<td>7</td>
</tr>
<tr>
<td>NO</td>
<td>14</td>
</tr>
</tbody>
</table>

The source has also been mounted on the accelerator source stand and the beam has been accelerated and used on target for experiments with reliable results. The final version of the source is now being constructed.

**Power Supplies**

The source requires the following power supplies: Arc, extraction, focus, 5º magnet, ion pump, and two filament supplies. These supplies are in various stages of completion and have not yet been tested as a unit. However, all types of components used have been tested under both pressure and vacuum. Reliability is very important in this section of the source. Several measures have been taken to reduce source failure. First, any one of the above supplies can fail and the source will still operate with the exception of the arc and ion pump supplies. Dual filaments and filament supplies allow switching to the second filament if the first fails. The extraction and focus supplies are commercial units already tested in a terminal environment.

About 15% of the maximum source beam is available even if the focus supply is off. Due to the large H⁻ and D⁻ beams, the source can be run on these ions with no focus. If the extraction supply fails, a relay grounds the focus electrode and switches the focus supply to the source extraction electrode.
The 5° magnet will consist of both a permanent and an electromagnet. The permanent magnet will be set to bend protons 5° and the electromagnet will be used to bend heavier ions. Thus, if this supply fails, the source will still produce a usable proton beam.

A second reliability measure is overrating components as much as possible. In particular, solid state devices are overrated by factors of 10 to 20 or more.

As a third measure, inductance chokes are placed at each supply input and output terminal to prevent spark transients picked up on wiring from entering the supply. This method has proved successful in previous equipment installed in the terminal.

Source Controls and Readouts

The source controls and readouts have been completed and partially tested. Lucite rods driven by motors outside the accelerator tank will operate various and switches in the terminal to control the source. This system is already in use in the accelerator. Meter readouts will employ light-emitting diodes in the terminal to transmit a light beam whose intensity represents the parameter being measured. At ground, a light-sensitive transistor will receive the light and operate a meter on the control console. In some cases, the diode can be driven directly from the power supply being monitored, while in other cases, a transistor amplifier is used. A single channel prototype unit has operated successfully in the accelerator terminal and the ten channel unit is complete and has been bench tested.

The entire source will be assembled on a wooden mockup of the accelerator terminal in the future, and tested extensively as an entire unit. A pressure vessel large enough for the entire source is available and will be used for additional testing.

2. See Sec. 1.2 of this Report.

2.2 Fast Periodic Polarization Flip Modification to the Polarized Ion Source

E.G. Adelberger, M.D. Cooper, and H.F. Swanson

The Polarized Ion Source in its present form is shown schematically in Fig. 2.2-1. A neutral hydrogen beam is produced with nuclear spin parallel to the beam axis. A 90° rotation by the Wien filter gives a horizontally polarized beam, and a further rotation of 90° about the beam axis by the spin flip solenoid achieves vertical polarization. Following the suggestion given in last year's Annual Report, beam polarization is reversed by reversing the direction of the quench and argon fields, which reverses the direction of the hydrogen's nuclear spin with respect to the beam axis. Thus steering effects are minimized as the beam is uncharged through most of its travel in these fields. The theory of operation is amply explained in previous Annual Reports.
Fig. 2.2-1. Polarized Ion Source

A switching bridge was chosen to reverse the current in the quench and argon coils and is shown schematically in the bottom of Fig. 12.2-2. Identical circuits are used for both the quench and argon coils. Voltage and current limitations of available bridge components set a minimum limit on the time required. Switch the 575 Gauss quench field to about 10 milliseconds. This switching at a rate up to 10 times a second can be achieved without appreciable dead time. Two Kepco high speed programmable power supplies were purchased, a 0-75 volt, 0-15 amp and a 0-75 volt, 0-7 amp for the quench and argon coils respectively, which are programmed in the constant current mode. The existing quench and argon coils were wound on brass bobbins and the former were made integral with the beam tubes. Eddy current generated during switching extended the transient times to unacceptable values and new coils were wound on split forms to minimize these effects. In addition, new beam tubes of thin walled stainless steel were made to provide a high resistance path to these currents.

A light pipe system is used to communicate with the bridge as the source is elevated to a negative 45 kV above ground. This is driven by an accurate period generator as shown in the top half of Fig. 12.2-2. The output of a 5 MHz crystal oscillator is first divided by 5 and then by 5 decade dividers using SN 7490's to achieve a longest period of 1 second. A variable period is obtained by modifying one or more of the decade dividers to divide by 1 through 10 by decoding their binary output with an SN 7442 BCD to decimal decoder and resetting the respective divider on the first through the tenth count, respectively. Two decades of control are obtained by decoding two of the decade dividers and requiring a coincidence of both decoded numbers to reset the dividers. The period reproducibility of such a system, once temperature equilibrium is achieved, is one oscillator period or parts in 10^6.

The output is divided by two to provide two state logic for routing and driving the bridge. It also triggers a timing monostable multivibrator which is called VGO (variable gate off). A coincidence between the monostable's normally high output and the experiment control "flip flop" is required to provide start and stop signals for the counting rooms and gates them off during the switching transient. With this control, an experiment is started and stopped only at the beginning of a complete period.

Work is in progress to install the new beam tubes and complete an accurate alignment.
2.3 Sputtering-Type Ion Source for the Production of Negative Heavy Ion Beams

J.G. Cramer and C.F. Linder

A sputtering-type ion source similar to the UNIS source described by Middleton and Adams has been designed and is now being built. It employs the same optical bench construction which has previously been used at this Laboratory for the potassium source and the lithium-helium source. Since the source employs many optical elements which have already been constructed, its fabrication will be simple and relatively cheap, involving an incremental cost of about $500 including shop time.

The principal differences between the present source and UNIS are as follows: a) The source will use cesium instead of potassium as the sputtering agent. This is because of the anticipated increase in efficiency and lower operating temperatures anticipated with cesium and the experience that we have had with both cesium and potassium in ion sources at this Laboratory. This experience indicates that cesium is far safer to handle than potassium during loading and cleaning operations. b) The source will include a focus element between the
cesium extraction electrode and the sputtering cone. This will allow the sputtering beam to be systematically set to illuminate the sputtering cone so as to produce the maximum beam. It should also eliminate the necessity of the 8" flight path needed by Middleton to allow the beam to spread enough to illuminate the sputtering cone optimally, thus resulting in a more compact source. c) The porous tungsten ionizer will be electron-beam welded to a molybdenum holder and heated directly. This should result in more efficient heating and less cesium loss than the radiant heating technique mentioned by Middleton.1

Components of the source are now being fabricated and testing should begin in about six weeks. First priority will be given to obtaining a high intensity carbon beam.


2.4
A Hollow Cathode Arc for Ion Sources

F. Weiss and W.G. Weitkamp

Richards and Klody1 have demonstrated the feasibility of using a hollow cathode arc as a source of electrons for a duoplasmatron ion source. The primary advantage of a hollow cathode arc over the usual heated filament is ruggedness. A hollow cathode is expected to require much less frequent replacement than a filament. For this reason we have investigated the properties of a hollow cathode arc with the intention of incorporating it into existing ion sources in the Laboratory.

The apparatus presently in use is shown in Fig. 2.4-1. Argon gas is fed into the hollow cathode, where heat produced by ion bombardment on the inner walls causes sufficient electron emission to sustain a stable discharge. The electrons from this primary arc are used to maintain a secondary arc in any desired gas.

Considerable difficulty has been encountered with arcing outside the cathode, resulting in rapid erosion of the cathode. This unwanted arc has been successfully suppressed by the boron nitride shield shown in Fig. 2.4-1.

This system starts easily, runs stably, and has produced secondary arcs in both helium and nitrogen, as well as argon. Plans call for installation of a zwischen electrode and an aperture in the secondary arc region in order to convert the apparatus into a usable ion source.
Fig. 2.4-1. Schematic drawing of the hollow cathode arc apparatus.

3. INSTRUMENTATION AND RESEARCH TECHNIQUES

3.1 Computer Controlled Target Elevator for Precision Measurement of Excitation Functions

J.C. Cramer and N.G. Ward

Accurate measurement of excitation functions is frequently plagued with inconsistencies and problems of reproducibility due to changes in beam position, target warping, carbon buildup on the target, or loss of target material from one energy step to the next in the excitation function. We have encountered particularly difficult problems in measuring excitation functions with polarized beams where the beam intensity is sufficiently low that tight collimation of the beam is undesirable. We have therefore developed a system whereby up to 40 keV of an excitation function can be measured at the same time, with essentially fixed target and beam conditions. This is accomplished by repetitively changing a voltage applied to the target through a range of ±20 keV while holding the beam energy fixed.

This is accomplished through the use of the target elevator, which is essentially an operational amplifier with a gain of 2,000, a maximum output voltage of ±22 V, a transient current limit of 0.8 mA, and a minimum slewing time of 100 microsec for voltage steps of 500 volts or less. This device is connected to the D/A output (±10 volt max) of the computer (see Sec. 5.1B) so that the voltage steps applied to the target are set by the computer program, depending on the range and step size which is appropriate to the excitation function being measured.

The bipolar output of the target elevator is derived from a pair of Spellman DC-to-DC converters, one positive and one negative, which are regulated through a pair of 6BK4 regulator tubes. The tubes are controlled by phototransistors in their cathodes, which are optically coupled to LED's in the low-voltage control circuitry through light pipes which provide the necessary voltage isolation. The high voltage output is sensed with a Tektronix P6015 high voltage probe which delivers a low voltage replica of the output with good frequency response. The feedback signal incorporates not only the output but also its time derivative in order to insure a stabilized minimum setting time.

3.2 Bunched Beam Timing Stabilizer

D. Oberg

The klyston beam buncher has been used in experiments requiring time-of-flight information, e.g., $E^2$ mass identification. This timing information is obtained as the difference in the time between the buncher stop signal and the fast timing signals from the detected events which are presented as stop and start signals to time-to-amplitude converters (TAC) and then to the computer via the analog-to-digital converters (ADC).

The stability of this timing information is dependent upon the stability
of the transit time of the particles through the Van de Graaff from the ion source to the scattering chamber, and on the buncher tuning. The transit time depends on the Van de Graaff terminal voltage and on the extraction voltage of the ion source. Thus the transit time will change during the taking of excitation functions, during extraction voltage fluctuations, and when there is 60 Hz ripple present in the extraction voltage.

The stabilization is accomplished by using a reference timing signal obtained in the same fashion as the normal signal, except using a separate detector gated to accept only monoenergetic (elastic) events. The TAC and ADC gains are adjusted to give the same timing calibration for the two systems. Except for a constant, the time-of-flight for the event of interest is then just the difference between its timing and that of the reference system, as each is equally affected by transit time variations.

This correction information must be averaged over a sufficient number of events in the computer routine to minimize statistical fluctuations, while at the same time the timing lag between the instantaneous average correction and the instantaneous correction must be small compared to fast variations, e.g., 60 Hz. These requirements necessitate high count rates, which will not increase the computer dead time if a lower priority interrupt is used.

In use, this system has improved the data-taking efficiency, by eliminating the need for continual readjustment of the timing, and has reduced the effects on time resolution of 60 Hz ripple, source voltage drifts and buncher changes.

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2. Section 7.1 of this Report.

3.3 Design and Construction of Electronic Equipment

L.H. Dunning, H. Fausska, R.E. Stowell, and N.G. Ward

Major electronic projects are discussed in Sec. 1.2 and Sec. 3.1 of this Report. Additional projects completed during the last year include:

a. An inverter providing 1.2 kW of 400 Hz power to facilitate terminal ion source testing was designed and constructed.

b. An ion source test magnet regulator was constructed.

c. A regulator to reduce long term drifts in the extraction voltage of the polarized ion source was designed and constructed.

d. A dual magnet reversing system was designed and installed on the polarized ion source (see Sec. 2.2).

e. The Wein filter supply on the polarized ion source was redesigned, constructed and installed.
f. A digital panel meter with amplifier was installed on the control console of the Van de Graaff.

g. A routing system was constructed and installed on the two Northern Scientific analog to digital converters of the computer.

h. An electronic rabbit dwell timing sensor and recorder was designed and constructed.

i. A portable magnetometer of the Hall type was designed and constructed.

j. An electron gun calibrator, a three-coordinate Helmholtz regulated supply, a buffer amplifier and calibrator for a target elevator, two pre-amplifiers and an ion gauge controller were designed, constructed, and installed on the Auger electron experiment beam line (see Sec. 4.6).

k. A second ion gauge controller was constructed.

l. Two charge-sensitive pre-amps were constructed.

m. A polarity inverter and switch was designed and added to the retriggerable detector simulator pulse generator.

n. The following items were constructed for the Medium Energy Experimental Program: Two photomultiplier tube bases, a 200 MHz pulser with scaled down outputs, a fast risetime pulse generator and light emitting diode drivers (see Sec. 15).

3.4 Target Fabrication

J.M. Heagney

Approximately 275 targets and special degrader foils were prepared this past year, a 50% increase over the previous year. The tandem stripper foil wheel containing 39 5 µg/cm² carbon foils was filled and changed five times. Thinner carbon foils were used in order to improve machine performance.

Special ¹²C foils, 50-100 µg/cm² thick, were fabricated by electron bombardment from carbon of 99.987+% enrichment (highest enrichment available commercially is 99.9%). To prepare a target of this purity very highly enriched carbon dioxide was obtained from Los Alamos Scientific Laboratory and converted by Mound Laboratory into amorphous carbon.
4. DETECTOR SYSTEMS

4.1 Silicon Detectors

S. Kellenbarger

We continue to make our own lithium-drifted silicon detectors and most of our surface barrier fission fragment detectors. The majority of the Si(Li) detectors in use a year ago are still performing satisfactorily. Rectangular Si(Li) detectors are being made for the new "sideless" mounts.\(^1\)

In manufacturing Si(Li) detectors, we finish by evaporating either gold or aluminum on the center of the lithium diffused area. Contact to this is by a pin held by a spring. On part of the detectors we have cemented a disc of silver to the evaporated gold or aluminum using a conducting epoxy. The spring-held pin then rests on this silver. Inconclusive evidence indicates that detectors made with the silver disc are giving more reliable and longer service with fewer noise problems than those made without.

Surface barrier detectors were made for the special counter used to detect delayed fission fragments.\(^3\) With 50 volts bias, these detectors have a depletion depth of about 70 microns, thin enough so that the background particles deposit appreciably less energy in them than do the fission fragments.

1. Section 4.4 of this Report.
2. ENT-105 manufactured by Chomerics, Inc., 77 Dragon Court, Woburn, Mass. 01801.

4.2 10"x10" NaI Crystal Spectrometer

M. Hasinoff\(^*\), S.T. Lim\(^*\),
D.F. Measday\(^*\), and T.J. Mulligan\(^*\)

It is now common practice to use large NaI crystal for the detection of gamma-rays in the energy range 10 to 40 MeV. The University of British Columbia NaI crystal spectrometer design is illustrated in Fig. 4.2-1. The central NaI(Tl) crystal is a cylinder 25.4 cm in diameter and 25.4 cm long, hermetically sealed in an aluminum can; it was manufactured by the French company Quartz et Silice at St. Pierre les Nemours. The crystal is viewed by seven 78 mm phototubes of the type EMI 9758B, which has a 65 mm bi-alkali photocathode and an anode pulse rise-time of about 12 nsec.

Fig. 4.2-1. Design for UBC NaI crystal spectrometer.
The original phototubes were matched for gain but one was broken in shipment and the replacement tube had considerably greater gain. However the overall performance of the system does not seem to have been adversely affected. The voltage on the bleeder chain is adjusted so that the outputs of the phototubes are the same for a well collimated gamma-ray source incident on the front face.

A vital parameter of the performance of such a crystal is the uniformity of the response to a collimated gamma-ray source at different points parallel to the axis of the cylinder. The results of our tests show that the response to a 1.33 MeV gamma-ray from $^{60}$Co is uniform to ±0.75%. Further useful information is that the resolution for a $^{137}$Cs $\gamma$-ray (0.662 MeV) is 9.5% and the peak to valley ratio for the $^{60}$Co $\gamma$-ray was 3.3 for the factory tests although the best that we have obtained is slightly worse ($\approx$ 3.0). The difference is probably due to the replacement phototube.

Surrounding the sides and front face of the NaI crystal is a 1 cm thick neutron absorber composed of lithium carbonate in wax. A mixture with $\approx$ 70% by weight of lithium carbonate is sufficiently strong to support itself.

The anticoincidence shield consists of Ne 110 plastic scintillator, 10.8 cm thick, manufactured by Nuclear Enterprises of San Carlos, California. The scintillator Ne 110 was chosen as it has better light transmission than the more common Ne 102A and is only 10% more expensive. The thickness of 10.8 cm was chosen to match the photocathode of the 12.5 cm diameter RCA 8055 photomultiplier tubes.

Two Ne 110 discs were produced to test their usefulness for the front face of the crystal. Each was 50.8 cm in diameter; one was 10.8 cm thick (with RCA 8055 tubes) and the other was 6.4 cm thick (with Philips XP 1030 tubes). There is very little improvement in the system performance when the thicker one is used although this is the normal practice, even though it absorbs more of the incident gamma-rays. A test was tried using the thin disc at the front of the NaI and the thick one at the back but no difference could be found, so no scintillator is now used at the back.

The overall resolution (3.2% FWHM) obtained with this spectrometer is excellent as can be seen in the $^{12}$C(p,p') spectrum of Fig. 4.2-2 or in the $^{39}$K(p,γ) spectrum in Sec. 12.9. This resolution is probably due in part to the excellence of the NaI crystal supplied to us by Quartz et Silice but the use of 7 matched phototubes rather than one large phototube (60 AVP) most certainly also contributed by reducing the non-uniformities which are found in a large photo-cathode. We note that a similar NaI spectrometer constructed by Suffert et al.1 using a 10"φ × 12" NaI (Quartz et Silice) and one 60 AVP phototube gives slightly worse resolution, namely 4.7% resolution at $E_\gamma = 23.5$ MeV.

* Department of Physics, University of British Columbia.
Fig. 4.2-2. Gamma ray spectrum produced in the $^{12}\text{C}(p,p'\gamma)$ reaction.

### 4.3 Development of an Ultra-Thin Secondary Electron Counter for Time-of-Flight Mass Identification of Heavy Ions


We have investigated the efficiency and time resolution of a counter consisting of a thin carbon foil (5-20 μg/cm$^2$) and a channel electron multiplier (CEM). The foil is at a negative bias voltage (∼100 volts) with respect to the CEM, so that the latter detects some fraction of the low energy secondary electrons which are ejected from the carbon foil when a charged particle passes through it. The detection signal from the CEM can then be used to time the flight of the particle to a detector which measures its energy. The latter can be either a solid-state detector or a magnetic analyzer. The mass resolution $\Delta m/m = 2\Delta t/t$, so the time resolution of the device is quite critical.

At present we have tested a "funneltron" CEM, i.e., a helical CEM with a
funnel-shaped entrance aperture. This device has proved relatively unsatisfactory, in that the best time resolution obtained was about 4 ns. It was determined that the CEM was producing this time spread by studying the timing characteristics with a pulsed beam having a width of about 1 nsec. We will continue these measurements with other CEM's in an effort to obtain better time resolution.

The present measurements have revealed that the secondary-electron detection technique can be surprisingly efficient, even with ions as light as protons. At 3 MeV/nucleon we have found the following efficiencies for the detection of a charged particle passing through the carbon foil: ¹H, 36%; ²H, 39%; ⁴He, 86%; ¹⁶O, 100%. Thus almost all heavy ions of interest can be detected with nearly 100% efficiency, and lighter ions can be detected with reduced but acceptable efficiencies.

4.4 Development of "Sideless" Si(Li) Detectors For Use in Detector Arrays

J.S. Cramer and S. Kellenbarger

In nuclear physics experiments, particularly those with low cross sections or counting rates, it is frequently desirable to use an array of counters to increase the data input rate. If large solid angles are required or if the cross section decreases rapidly with angle it is often desirable to place the detectors in such an array as close together as possible. The usual limitation on doing this is the fabrication of the solid-state detector, which usually has a fairly large distance between the physical edge of the case and the edge of the sensitive surface of the detector. We have constructed detector cases which are designed to minimize the thickness of the detector sides so that the distance between the edge of the active surface and the edge of the case is only 1/16 inch. This case design is patterned after a design by N.R. Fletcher for an ⁸Be array detector¹ and is illustrated in Fig. 4.4-1. Table 4.4-1 gives the detector target distance \( l \) and the solid angle \( \Omega \) for an array of detectors of this design with an angular spacing \( d\theta \) between detector centers. As indicated, quite reasonable solid angles can be achieved even with detector spacings as small as 1°. These detectors are expected to be very useful, both in heavy ion measurements and in a silicon polarimeter which is now being designed² for determining proton polarization.

Table 4.4-1

<table>
<thead>
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<th>( \theta ) (degrees)</th>
<th>( l ) (inches)</th>
<th>( \Omega ) (millistr)</th>
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</thead>
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<tr>
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<td>2.62</td>
</tr>
<tr>
<td>1</td>
<td>25.85</td>
<td>0.66</td>
</tr>
</tbody>
</table>

2. See Section 10.2 of this Report.

Fig. 4.4-1. Sketch of cases for "sideless" Si(Li) detectors.
4.5 Modification of the Position-Sensitive Proportional Counter for Heavy Ion Detection in the Spectrograph

J.G. Cramer and M.J. Leich

The single-wire position sensitive proportional counter described in the 1971 Annual Report is currently being modified to make possible its use in heavy ion experiments. These modifications are: (1) The entrance window will be made thinner. Windows are being made from two or three layers of 0.3 mil mylar. (2) A gas regulator will be added to the gas handling system so the counter can be pressurized to less than 1 atmosphere. Since heavy ions produce more ionization in the counter, less pressure is needed and thinner windows can be used. (3) A better time signal is needed than can be obtained from the position-sensitive proportional counter due to the characteristically long rise times of this device. Therefore, a second thicker proportional counter is being added behind the first to provide better time and energy information. These modifications are now in progress, and test with heavy ions in the spectrograph will begin soon.


4.6 Apparatus for Detection of Auger-electrons and X-rays

D. Burch, H. Fauska, W.B. Ingalls, and J.S. Risley

A differentially-pumped gas-target scattering chamber has been constructed for experiments in which Auger-electrons and x-rays are produced through ion-atom collisions. A schematic diagram of the apparatus is shown in Fig. 4.6-1. Target pressures as high as 50 mTorr can be used while the pressure in the beam line and analyzer chamber is maintained in the 10^{-6} Torr range. Target pressures are measured with a Baratron capacitance manometer. Absolute pressures can be determined, independent of target gas, to within ±5% and are monitored digitally in the Counting Room. Target gas is emitted through a Granville-Phillips leak which is maintained on the high pressure side at 400 Torr with a vacuum regulator. This system has proved very satisfactory; after 20 min. the pressure variation is less than 5% per day.

Electrons are energy-analyzed with a cylindrical-mirror electrostatic analyzer and detected with a channel electron-multiplier. The base resolution (without deacceleration) is 1.4% FWHM. The effective solid angle of the analyzer is 3.9 \times 10^{-4} cm\text{-}sr. The voltage insulation permits the analysis of electrons with energies up to 5 keV. At present, it is suspected that the absolute transmission efficiency is erroneously low for electrons with energies below ~ 50 eV. The energy resolution is not affected, however.

The analyzer is operated automatically in a sweep mode. Any voltage range of interest with a width of 50 to 2000 V is established with an off-set triangle
generator and operational amplifier. This voltage is applied directly to the analyzer. A corresponding signal of 0-10 V is also generated which is fed into the dc input of the ADC. The ADC is operated in the coincidence mode with the gate signals provided by the channeltron output. A built-in calibration system provides a convenient means of setting up the desired sweep range. Typical sweep rates are 10 cps which effectively results in a non-dispersive accumulation of the spectrum.

X-rays are detected with a thin-window gas-flow proportional counter which has an effective solid angle of up to $3 \times 10^{-2}$ cm-sr. A "foil attachment", which is used for detector-foil transmission measurements, is incorporated into the system. The second small chamber contains a positively biased Au-foil target and a Si(Li) particle detector which is used to monitor heavy-ion beam intensities.

The system is iron-free in the region within 3 mutually perpendicular pairs of Helmholtz coils, each 5 ft. in diameter. The residual magnetic fields in the region of the analyzer are <15 mG. It has been found that magnetic fields of ±75 mG from zero have no effect on the detection of electrons above 200 eV.

The beam-pipe section just before the scattering chamber can be replaced with a 0-10 keV, 50 µA electron gun. In this manner, electron yields from heavy-ion collisions have been compared to identical measurements using incident electrons.

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Fig. 4.5-1. a) Schematic diagram of the apparatus, not shown to scale. Individual components are discussed in the text. b) The cylindrical-mirror electrostatic analyzer. The "field-straightening" plates are not shown.
5. COMPUTER SYSTEMS

5.1 Computer System Improvements

N.R. Cheney

A. Memory Expansion

A 16K word memory chassis has been installed in the Laboratory's off-line computer, increasing its memory capacity to 32K words. A similar unit is being readied for the on-line computer to bring its memory size to 32K words.

B. D/A Converter Addition

A 12 bit digital to analog converter was added to the on-line computer as a general purpose analog output device. The unit has a conversion time of > 10 usec, output range of ±10V max, and is accurate to ±0.25%. The output range is controlled by adjustable reference voltages.

C. Jobs in Progress

Analyzer Interface. Two pulse height analyzers recently acquired by the Laboratory are presently being interfaced to the on-line computer. The interface allows flexible control of the analyzers by the computer, start/stop control from scalers, as well as the normal transfer of data. Checkout of this hardware is nearing completion.

Additions to Off-Line Computer. Several units are being added to the off-line computer so its hardware configuration will more closely duplicate that of the on-line computer. The purpose is to improve software compatibility between the two machines. The units being added include: (1) Dual channel TMCC (I/O buffer) to replace the Single Channel TMCC presently in use; (2) Priority Interrupt chassis (16 levels of interrupt); (3) Interrupt Arming chassis. The chassis have been installed but must undergo a final checkout before they become operational.

New Card Reader for On-Line Computer. An improved version of the card reader designed and fabricated by the Laboratory a number of years ago is being built for the on-line computer. It will replace the original reader which has been in service for 6 years. The operation of the original reader is still satisfactory; however, the performance of the reader used with the off-line computer (an improved version of the original design) justifies the replacement.

Incremental Plotter. A used calcomp model 565 incremental plotter and coupler has been acquired from Xerox Corporation. The unit will be installed for use with the off-line computer.
5.2 CALIBAN, A Program for Computer-Controlled Calibration and Gain Matching of Preamplifier-Amplifier-SCA-ADC Systems

J.G. Cramer

The addition to the computer system of a general purpose digital-to-analog D/A converter\(^1\) has made it possible for the first time to operate a pulser under computer control for the purpose of systematically calibrating preamp-amp-SCA-ADC systems used in data collection. A program has been written and debugged which can be used to calibrate routinely such systems with a controlled pulser and establish the gains, energy scales, zero intercepts, linealities, and upper and lower cutoffs of all such systems being prepared for data collection.

The operation of the program is as follows: The Berkeley Nuclearonics Pulser Model DB-2 is controlled by the on-line computer, which provides the pulser with an external reference voltage from the D/A converter and an external trigger pulse from the multiplexer. The pulser output is connected to the input of the ORTEC Dual-decade Attenuator and the controls of the pulser are set in standard positions so that when the reference voltage from the D/A is exactly +10 volts the settings of the 422 read directly in MeV. The two 422 outputs are then connected through their charge terminators to the inputs of the preamplifiers of two systems to be calibrated. The pulser then produces a programmed sequence of pulses under computer control and the response of the ADC's to these pulses is recorded by the program. From analysis of the pulser commands and the ADC responses the program computes the calibration parameters repetitively. These parameters (gain, zero crossing, linearity) are displayed on the nixie readouts of the on-line computer. This permits adjustments of gains, zero settings, SCA windows, etc. in real time as the program cycles through the calibration procedure. Since two systems are calibrated at once, gain matching for such devices as counter telescope systems becomes quite straightforward.

The program also has modes which permit the following operations:

Mode 1: Find ADC system calibrations as described above.
Mode 2: Sweep pulser between limits set by digit switch 1 and digit switch 2. This is very useful for various testing operations.
Mode 5: Plot pulser output against ADC response. This is useful for graphically displaying cutoffs and non-linearities, e.g., amplifier saturation.
Mode 6: Print out a summary of the calibration constants of the two ADC systems on the line printer. This provides a hard copy of the calibration results for use in analyzing data after the run.
Mode 7: Punch out calibration summary cards. This permits the results of the calibration to be loaded in as part of the initialization of a data collection program which can use them subsequently.

The program is now operating reliably, and has been successfully used for pre-run calibrations. The reference supplies of the D/A converter had shown some drifts which limited the use of the calibrations, but new reference supplies have been installed and this problem has now been corrected.

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1. See Sec. 5.1B of this Report.
5.3 A Three ADC Event Recording Program with On-Line Sorting

E. Schnellman and J.W. Tape

A program has been written for the 930 on-line computer system which allows the user to record three-parameter coincidence data on magnetic tape on an event by event basis. The spectrum from each ADC can be displayed on line to monitor the progress of the experiment. In addition, data from one ADC can be sorted into different spectra according to digital windows set on the other two ADC's. The program will initially be used for gamma-gamma coincidence experiments.

5.4 Monte Carlo Efficiency Program

D.D. Chamberlin and D.L. Oberg

In a coincidence experiment the detection probability for the recoil particle, given the detection of the scattered particle, depends upon a variety of independent factors. These involve geometric positions within the target beam spot and over the surface of each detector and distribution functions representing multiple scatter or relating the recoil momenta directions from successive gamma-ray emissions from the excited recoil nucleus. We have written a computer program which assigns values for these variables from an internally generated list of random numbers, calculates the flight path of a recoil nucleus for these values and, after a large number of trials, computes the collection efficiency. As the calculation gives all parameters for each event, it is possible to extract a detailed distribution of recoil particle energies as a function of recoil position. The XDS 930 computer requires about 15 minutes to execute 5,000 trials.

5.5 Search Program for Proton Elastic Scattering Analyzing Power Measurements Near Isobaric Analog Resonances

M.P. Baker

A FORTRAN II program has been written which is designed to fit simultaneously proton elastic scattering analyzing power and differential cross section excitation functions by a $\chi^2$-minimization searching procedure. The scattering amplitudes include both direct and resonant terms. The direct scattering is parameterized using energy-dependent polynomials while the resonance contributions have the usual Breit-Wigner form. The program simultaneously fits excitation function data for the differential cross section and the product of analyzing power and differential cross section. The search routine combines the features of the usual gradient search and the method of linearizing the fitting function as given by Bevington.¹ One hundred energies may be fit and as many as 43 parameters varied simultaneously. At the conclusion of a search, the excitation function data and fits are plotted for easy comparison.

5.6 Program for Generation of Proton Elastic Scattering Excitation Functions Over Isobaric Analog Resonances

M.P. Baker

A FORTRAN II program has been written that generates proton elastic scattering analyzing power and differential cross section excitation functions. The scattering amplitudes include both direct and resonant terms. The direct terms are calculated from standard optical model parameters while the resonance contributions have the usual Breit-Wigner form. Excitation functions are generated at as many as 100 energies for three scattering angles. However, only twenty partial waves can be included in the scattering amplitudes. Data may be read in and plotted with the results at the conclusion of the calculation.

5.7 Modification of the Program DWUCK for Sub-Coulomb Transfer Calculations

K.G. Nair

Modifications have been introduced in the DWBA program DWUCK\(^1\) for the calculations of cross sections for the sub-Coulomb and near-Coulomb single nucleon transfer induced by heavy ions, based on the theory of Buttle and Goldfarb.\(^2\) Provisions in the modified version include choice of representation, Coulomb correction terms in the form factor and approximate corrections for the neglect of recoil.

1. P.D. Kunz, University of Colorado, unpublished.
6. STRUCTURE OF AND REACTIONS ON LIGHT NUCLEI

6.1 An Attempt to Measure the Alpha Branching Ratio of the 15.11 MeV State in $^{12}$C

E.G. Adelberger and J.E. Bussoletti

The isospin violating branching ratio for alpha decay from a $T = 1$ initial state to a $T = 0$ final state measures the size of charge dependent interactions in nuclei. When the isospin impurity in the $T = 1$ state can be ascribed to the mixture of a single $T = 0$ state, the charge dependent matrix element connecting the unperturbed states can be obtained in a straightforward fashion from the alpha branching ratio. The situation in $^{12}$C, illustrated in Fig. 6.1-1, is particularly simple. The 15.11 MeV and the 12.71 MeV states essentially exhaust the $1^+$ strength in the lp shell. The next set of $1^+$ states must have the configuration $[(sd)^2\, (p^0)^{-2}]$ and will be far removed in energy from these states.

The size of the charge dependent matrix element between these two $1^+$ states has been measured by two different reactions and a consistent result obtained.1,2 Several measurements (or upper limits) of the alpha decay of the 15.11 MeV state exist,3-6 of which the most precise6 led to a result nearly equal to the size of the matrix element as measured in Refs. 1 and 2. However, a recent experiment by Alburger and Wilkinson7 indicated that the result from the alpha branch measurement may be incorrect due to an error in the size of the gamma branch from the 15.11 MeV state to the 12.71 MeV state. The fact that the charge dependent matrix element measured by Braithwaite and Cecill1 and Braithwaite et al.2 is the largest such matrix element (approximately 240 keV) ever measured that is not subject to complications due to the admixture of a third state suggests that a further independent measurement of this matrix element would be of considerable interest.

A measurement of the alpha branch of the 15.11 MeV state was undertaken by populating the $^{12}$C(15.11) state through the reaction $^{10}$B($^3$He,p)$^{12}$C and then detecting the coincident alpha particles. A 2000 micron lithium-drifted silicon detector at 0° was used to detect the protons. A degrader consisting of 1.0 mil aluminum, 0.3 mil titantium, and 6.0 mil mylar was used to stop elastic helions and alphas from the ($^3$He,$^3$He) and ($^3$He,α) reactions. The solid angle subtended by the proton counter was 75 mrad. A second lithium-drifted silicon detector was used at an angle of 125° (the zero of P2(cos θ)) to detect coincident alpha particles. The solid angle subtended by the alpha counter was 50 mrad. The targets
Figs. 6.1-2. Alpha spectrum in coincidence with proton groups.

were self-supporting enriched $^{10}$B targets and were 50 mg/cm$^2$ thick.

An investigation of singles proton spectra revealed that $^3$He particles dence with decay alphas.

at an incident energy of 3.5 MeV produced the least background in the proton spectra. Thus our measurements were performed with a 3.5 MeV $^3$He beam of about 50 nA intensity. During a run of about two hours (a 1.7 mC of accumulated charge) coincidence spectra were obtained.

Spectra of decay a-particles are shown in Fig. 6.1-2. No background subtractions have been made. It is clear that the a's in coincidence with protons from the formation of the 15.11 MeV state are mostly due to the continuous proton background under the 15.11 MeV peak (see Fig. 6.1-3). A comparison between the coincidence proton spectrum (Fig. 6.1-3) and a singles proton spectrum yielded an alpha branch for the 15.11 MeV state of 9% ± 7% after normalization to a 97.1% branch for the 12.71 MeV state, subtraction of a 0.5% accidental rate and correction due to a 1.5% gamma branch from the 15.11 MeV state to the 12.71 MeV state. The large error in the alpha branch measurement is due to the proton continuum beneath the 15.11 MeV peak. There may be additional errors due to contaminants in the 15.11 MeV singles peak from the reaction $^{12}$C($^3$He,p)$^{14}$N(g.s.).

A calculation of the ratio of the penetrabilities for the alpha decay of the two states, combined with the 9% branch implies a mixing amplitude $\beta = 0.16 \pm 0.13$, in agreement with the result of Braithwaite et al. which yielded $\beta = 0.11$. Further measurements will be made in an attempt to reduce the error in the measurement.
6.2 Isospin Mixing in $^{16}$O in the Vicinity of the Lowest $T = 2$ State

E.G. Adelberger, J.E. Bussoletti, J.R. Calarco, F.S. Dietrich, and A.V. Nero

We have continued to study the mirror reactions $^{12}$C$(\alpha, n_0)$ and $^{12}$C$(\alpha, p_0)$ in an attempt to understand isospin mixing in $^{16}$O. The excitation functions at $\theta_{cm} = 90^\circ$ have been extended. The proton data taken at the University of Washington covers the region from 20.24 to 23.26 MeV with angular distributions as 20.40, 20.64, 20.90, and 21.10 MeV (see Figs. 6.2-1 and 6.2-2). The neutron data extends over an even wider energy region in somewhat coarser steps (only a small

![Excitation functions](image)

Fig. 6.2-1. Excitation functions for the $^{12}$C$(\alpha, n_0)$ and $^{12}$C$(\alpha, p_0)$ reactions in the region of the lowest $T = 2$ state of $^{16}$O. The ordinate for the $(\alpha, p)$ data is in units of millibars/sr; for the neutron data the units are arbitrary. Only a small fraction of the $(\alpha, n)$ data is shown here. The unlabeled vertical arrows indicate energies where $(\alpha, p_0)$ angular distributions have been taken.
part of the \((a,n)\) data is shown in Fig. 6.2-1). They were taken with the pulsed-beam time-of-flight spectrometer at Stanford.

The original motivation for this work was to determine the nature of the isospin impurity of the lowest \(T = 2\) level in \(^{150}\)O -- to see if it is primarily \(T = 0\), primarily \(T = 1\), or some mixture of the two. Previous information\(^1,2\) about the decay properties of the \(T = 2\) state had revealed that the level has at least some \(T = 0\) impurity since \(a\) decays were observed. We felt that \(^{150}\)O was a good place to study isospin mixing because the shell closure should simplify calculations and the open neutron channel gives us a "handle" which is not available for the lowest \(T = 2\) states of heavier nuclei.

An essentially pure \(T = 0\) impurity can be distinguished from an essentially pure \(T = 1\) impurity by its interferences in the \(^{12}C(a,n)\) and \(^{12}C(a,p)\) reactions with a background overlapping broad resonances (see Figs. 6.2-1 and 6.2-2). If, for the sake of discussion, we assume that the background amplitudes are purely \(T = 0\) (isospin conserving) and that the resonant \("T = 2"\) amplitude involves isospin admixtures \(a\mid T = 0\rangle + \alpha\mid T = 1\rangle\) then

\[
\delta(a,n) \propto |A^\text{Back}_{a,n}|^2 + 2 \text{Re}(A^\text{Back}_{a,n} A^\text{Res}_{a,n})^* \\
\delta(a,p) \propto |A^\text{Back}_{a,p}|^2 + 2 \text{Re}(A^\text{Back}_{a,p} A^\text{Res}_{a,p})^*
\]

where

\[
\begin{align*}
A_{a,n}^\text{Res} &= A_{T=0}^\text{Res} + A_{T=1}^\text{Res} = C_1 \alpha^2 + C_2 \alpha \delta \\
A_{a,p}^\text{Res} &= + A_{T=0}^\text{Res} + A_{T=1}^\text{Res} = - C_1 \alpha^2 + C_2 \alpha \delta \\
A_{a,n}^\text{Back} &= - C_3 \\
A_{a,p}^\text{Back} &= + C_3.
\end{align*}
\]

Then in this case a pure \(T = 0\) resonance interfering with a \(T = 0\) background
should produce identical anomalies in the \((\alpha, n_0)\) and \((\alpha, p_0)\) channels while a
largely \(T = 1\) resonance should show interference anomalies of opposite sign in
the two channels.

We have studied the \((\alpha, n_0)\) and \((\alpha, p_0)\) reactions at \(\theta_{cm} = 90^\circ\). At this
angle even and odd spin compound states do not interfere. To see this note, that
for reactions of the form \(0^+ + 0^+ \rightarrow J^\pi \rightarrow 1/2^+\) to \(1/2^-\) parity invariance requires
that \(L_{out} = L_{in} \pm 1\) and hence channel spin \(S = 1\) in the outgoing channel. As a
result the reaction amplitudes take the form

\[
A = \sum_{J, M} a_J \gamma_J^M(\theta) \chi_1^{M}. 
\]

Since

\[
L^1_{even}(90^\circ) = L^0_{odd}(90^\circ) = 0, 
\]

the odd and even \(J\) have orthogonal channel spin functions.

Initial investigation of the two reactions in the immediate vicinity of
the lowest \(T = 2\) state had revealed that the anomalies of the \((\alpha, p_0)\) and \((\alpha, n_0)\)
resonances had opposite signs but almost equal amplitudes. If the background
is \(T = 0\), one may infer that the operative impurity is predominantly \(T = 1\). But
is the background \(T = 0\)? To check this we decided to study both reactions over
a fairly wide energy region. The previously observed narrow \(J^\pi = 5^-\) resonance
at 23.1 MeV appears as a dip in both reactions and the slope from \(E_x = 22.45\) to
22.75 MeV is similar in the two reactions. However the structures at \(E_x = 22.3\)
and 22.8 MeV have opposite signs in the \(n_0\) and \(p_0\) channels.

The excitation region studied is in the middle of the giant dipole reso-
nance. However at \(90^\circ\) the \(T = 2\) state should not interfere with \(L^-\) levels which
should simplify the interpretation. The current focus of this work is on understanding
the broad structures in the vicinity of the \(T = 2\) state, in particular
on the dipole resonances themselves. By combining the results of this study with
the \(^{12}_C(\alpha, o)\) work reported elsewhere in this progress report, one may be able to
learn a great deal about the isospin parity of the dipole resonances as well as
the character of the impurity of the \(T = 2\) state.

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   (1973).
3. Section 12.7 of this Report.
A Microscopic Analysis of the $^{6}\text{Li}(^{5}\text{Li, }^{6}\text{Li}^*(3.56))^{6}\text{Li}^*(3.56)$ and the $^{6}\text{Li}(^{6}\text{Li, He})^{6}\text{Be}$ Reactions

J.S. Blair, J.C. Cramer, and W.R. Wharton

The reactions $^{6}\text{Li}(^{5}\text{Li, He})^{6}\text{Li}^*$ and $^{6}\text{Li}(^{6}\text{Li, He})^{6}\text{Be}$ proceed to three members of the same $T=1$ isospin multiplet. Naive charge independence would predict identical differential cross sections, but Coulomb distortions and other effects produce significant differences. (Here $^{6}\text{Li}^*$ indicates the $T=1, J^T=0^+$ state state at 3.56 MeV excitation in $^{6}\text{Li}$.) The wave functions of the isomultiplet states have a configuration which is nearly identical to the $^{6}\text{Li}$ ground state except for a different spin-isospin coupling of the lp-shell nucleons, and it is expected that these reactions are quasi-elastic. Thus such reactions can be analyzed microscopically to obtain information on the spin-isospin-dependent effective nucleon-nucleon interaction in finite nuclei, in the same spirit as similar analyses of inelastic and charge-exchange reactions such as $(p,p'), (p,n)$, and $(^3\text{He},t)$. In the previous Annual Report we have presented experimental data for these $\text{Li}+\text{Li}$ induced reactions, giving angular distributions and excitation functions at laboratory bombarding energies between 28 and 36 MeV. We have analyzed the data with DWBA calculations employing microscopic form factors, as will be discussed below.

The $^{6}\text{Li}$ ground state has $J^T=1^+$ so that channel spin, $S$, (the vector sum of the individual spins) is 0, 1, or 2 in the $^{5}\text{Li}+^{6}\text{Li}$ channel. According to Bose-Einstein statistics and parity conservation, only the $S=0$ and 2 channels contribute to the $^{6}\text{Li}(^{5}\text{Li, He})^{6}\text{Li}^*$ reaction. Central forces between the two nuclei can contribute to the reaction only from the $S=0$ channel and tensor forces can contribute only from the $S=2$ channel. Tensor forces may mix channel spins 0 and 2 in the initial channel but otherwise channel spin is a good quantum number and the central and tensor forces contribute nearly incoherently to the reaction.

To calculate the microscopic form factors for the DWBA calculations, the nuclear states are described as good L-S coupled states and the interaction between the p-shell nucleons, indexed by $i$ and $j$ in each nucleus respectively, is

$$\sum_{i,j} V_{ll}(r_{ij})(\sigma_i \cdot \sigma_j)(\hat{t}_i \cdot \hat{t}_j) + \sum_{i,j} V_{Tl}(r_{ij})(\hat{t}_i \cdot \hat{t}_j)S_{12}.$$ 

These are the only parts of the central and tensor N-N interactions, respectively, which contribute to the reactions in a one-step process. Exchange contributions in which the full N-N interaction contributes are included by assuming a Serber potential. Form factors are obtained assuming either "knock-on" (K.O.) exchange in which only the two interacting nucleons may be exchanged or Full Exchange in which the p-shell nucleons in both nuclei are completely antisymmetrized with each other. Recoil corrections for the exchange terms are not included. The Majorana interaction is taken from the long range part of the Hamada-Johnston potential with the radial cutoff at 1.05 F. The tensor potential is chosen to have the OPEP form with a strength of 3.7 MeV obtained from the pion-nucleon coupling constant, 0.08. The $r^{-3}$ singularity in $V_{Tl}(r)$ presents no difficulty.

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since the tensor force contributes as $r^nV(r)$ at small interaction distances. Ten sets of optical potentials are obtained using Woods-Saxon shapes with widely varying parameters, and all sets give fair fits to the elastic scattering data between laboratory energies of 16 and 36 MeV.

Figures 6.3-1 and -2 show some of the calculations. The magnitude of the calculated cross section is determined by the strength of the N-N interaction but can be different by factors of two or possibly more for different optical potentials. Within this variation there is good agreement with the magnitude of the experimental cross sections. The inclusion of exchange terms involving non-interacting nucleons ("Full Exchange") increases the cross section by nearly a factor of two over the cross section obtained with just K.O. exchange terms. Traditionally most calculations include only K.O. exchange terms. The tensor force contributes less than 10% of the cross section. If the strength of the tensor potential is increased to about 8 MeV, the deep minimum at 80° in the $^6\text{Li}(^6\text{Li},^6\text{Li}^*)^6\text{Li}^*$ angular distribution would be filled in. This is taken as evidence against a strong tensor interaction, such as that used to analyze the $^{54}\text{Fe}(^3\text{He},t)^{54}\text{Co}$ reaction.

Most of the calculated angular distributions, using the various optical potentials, give good agreement with the data at center of mass angles greater than 35°, but all calculations do poorly at forward angles, giving a deep minimum at 15° (c.m.), whereas the experimental cross section is still rising at 17° (c.m.). The disagreement is more severe at 32 MeV than at 36 MeV and is similar to the anomaly found in the angular distributions of ($^3\text{He},t$) reactions. The experimental and theoretical excitation functions near 90° (c.m.) are in good agreement. Differences between the shape of the $^6\text{Li}(^6\text{Li},^6\text{Li}^*)^6\text{Li}^*$ and the $^6\text{Li}(^6\text{Li},^6\text{He})^6\text{He}$ angular distributions (shown in Fig. 6.2-3) are also explained by the DWBA theory. Much of the difference is due to the unequal Q-values for the two reactions. However, the experimentally determined ratio of magnitudes for the two reactions, $^6\text{Li}(^6\text{Li},^6\text{Li}^*)/^6\text{Li}(^6\text{Li},^6\text{He})$ is consistently 15% smaller than the theoretical value at nearly all angles and energies. This disagreement is probably a result of an incorrect $^6\text{Be}$ ground state wave function used in the microscopic form factor calculations.
Fig. 6.3-2. The DWBA calculations of the $^6$Li($^6$Li, $^6$Li*)$^6$Li* reaction using three different optical potentials are compared to the data at 36 MeV and the excitation function near 90° (c.m.). The calculations are made with: The optical potential used in Fig. 6.3-1 and full exchange (solid line); two other optical potentials and knock-on exchange (dashed and dotted lines).

In these calculations the $^6$He ground state, $^6$Li* (3.55 MeV) state and the $^6$Be ground state are assumed to have identical radial wave functions except for first order Coulomb corrections. Such an assumption severely underestimates the differences between these wave functions. In fact our wave function for the $^6$Be ground state is particle stable whereas the true $^6$Be wave function is unbound to $^6$He + 2p decay by 1.37 MeV.

The DWBA calculations have also been performed using a Yukawa potential of range 1.0 fm for $V_{11}$, with the strengths adjusted to match the magnitudes of the cross sections. The values obtained for $V_{11}$ are:

- $V_{11} = 7.2$ MeV with full exchange
- $V_{11} = 10.3$ MeV with K.O. exchange
- $V_{11} = 20.6$ MeV with no exchange.
Fig. 6.3-3. The ratio of the $^6\text{Li} (^6\text{Li}, ^6\text{Li}^*) ^6\text{Li}^*/^6\text{Li} (^6\text{Li}, ^6\text{He}) ^6\text{Be}$ differential cross sections is obtained at 32 MeV by fitting the experimental angular distributions with even Legendre polynomials (dotted line in (a)) and at 36 MeV by freely drawing lines through the data (dotted line in (b)). The DWBA calculations of the ratio (solid, dashed, and dotted lines) are the same as those described in Fig. 6.3-2 and the text.

The uncertainty in these numbers is 20% or larger\textsuperscript{10} and is primarily due to uncertainties in the optical potential. The values of $V_{ll}$ obtained from calculations of the (p,p'') reactions using K.O. exchange vary from 9 to 14 MeV\textsuperscript{11} and agree with the present results. This agreement is an indication that the use of microscopic form factors with an effective N-N interaction will eventually provide a consistent description of many inelastic and charge exchange reactions.

† Present address: Argonne National Laboratory, Argonne, Illinois.
2. Another microscopic analysis of the $^6\text{Li} (^6\text{Li}, ^6\text{Li}^*) ^6\text{Li}^*$ reaction has been completed. C.F. Clement and S.M. Perez, Nucl. Phys. A186, 561 (1972).
3. For a previous measurement of the $^6\text{Li}(^6\text{Li}, ^6\text{Li}^*) ^6\text{Li}^*$ reaction at 32 MeV see K. Nagatani, D.P. Boyd, P.F. Donovan, E. Beardsworth, and P.S. Assimakopoulos, Phys. Rev. Lett. 24, 675 (1970).
Fluctuation Studies in the Lightest Nucleus: Hydrogen

D. Carlson*, E. Johansson*, A. Lundby*, and F.H. Schmidt

During the academic year 1971-72, work was begun at CERN, in Geneva, on a search for Ericson-like fluctuations in the elastic scattering of charged pions by protons, the lightest, and presumably the simplest, of all nuclei. A preliminary report was given at the Divisional Meeting of The American Physical Society in Seattle; a more detailed paper will appear in Physics Letters.2

Aside from the energy range and the experimental techniques, the study of Ericson fluctuations in πp scattering bears a great resemblance to similar fluctuation studies in, for example, p-nucleus scattering. The physical interpretation and basis, as well as the theoretical formalisms are essentially the same.

There is, however, one great difference: For nuclei, one already knows that the phenomenon occurs, but for hadrons, its occurrence has yet to be definitely established.

It is of importance to answer the question for hadrons: First, statistical theories of hadron resonances essentially require that such fluctuations exist, and this would mean that the nucleon has a very complex structure. Second, if the fluctuations do not exist, then present theories are wrong and there is something about hadron "mechanics" which is very different from nuclear "mechanics".

To study elastic πp scattering, the experimental difficulties are substantially greater than for similar nuclear studies. Data existed on πp elastic scattering from an earlier experiment performed at 5 GeV/c pion momentum.3 Magnetic tapes of the scattering events were reanalyzed on a CDC 6400 computer at the CERN Laboratory. All events were divided into two groups of incoming pion momentum which differed by ~20 MeV energy in the center of mass system. Thus, the differences in cross-section between these two groups were found as a
Fig. 6.4-1. The asymmetry in cross-section between two momentum groups differing by ~20 MeV/c for $\pi^+p$ (upper curve), and for $\pi^-p$ (lower curve) elastic scattering as a function of $-t$. The ratio between the cross-sections is shown on the scale to the right. A center-of-mass angle scale is shown at the top for reference purposes.

function of scattering angle. The results are displayed in Fig. 6.4-1 for $\pi^+$ and for $\pi^-$ scattering. The parameter $A$ is the difference divided by the sum of the two cross-sections; $R$ is their ratio, where $R$ is positive when the higher energy group has the larger cross-section. The abscissa is in units of $-t$, the 4-momentum transfer. To aid in visualizing the results, a scattering angle scale is included at the top of the diagram.

We note that for $\pi^+p$ scattering, the cross-section changes very markedly with energy and angle, whereas for $\pi^-p$ scattering, the data indicate essentially no change outside statistical errors.

Unfortunately, so far as is known, no data exist at other closely spaced pion momenta in the mid-angular range. It is in just this region where one expects fluctuations to show up most strongly. It is not surprising that such data do not exist: The "run" on the CERN Proton-Synchrotron which generated the
events employed for the analysis shown in Fig. 6.4-1 required many months of operation.

On the other hand, other groups have measured $\pi^+ p$ scattering near 180° where the cross-sections rise very appreciably. Figure 6.4-2 shows a three-dimensional plot of $\pi$ scattering in the backward direction from about 1 to 3 GeV/c. It is remarkable to note that the changes in cross-section are very large. In fact, it is hard to escape the feeling that the system producing the scattering, the proton, is indeed a very complex structure.

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* CERN, Geneva.

3. V. Chabaud et al., Nuclear Physics, to be published.
7. NUCLEAR ASTROPHYSICS

7.1 Production of $^6\text{Li}$ and $^{10}\text{B}$ in the Proton Bombardment of $^{13}\text{C}$

D. Bodansky, D. Chamberlin, W.W. Jacobs, and D.L. Oberg

The investigation of the reactions $^{13}\text{C} + \alpha \rightarrow ^{10}\text{B}$ and $^{13}\text{C} + 2\alpha \rightarrow ^6\text{Li}$ is nearing completion. As described previously, the experimental procedure involves bombarding $^{13}\text{C}$ targets with the Van de Graaff bunched proton beam, and identifying the reaction products by an EIT² mass analysis. Data is collected in arrays of mass vs particle energy for $^4\text{He}$, $^6\text{Li}$, $^9\text{Be}$ and $^{10}\text{B}$.

Development of the bunched beam timing stabilizer allowed excitation functions to be taken in fine steps, without the need for continual manual readjustment of the timing system. Steps taken to reduce noise in the detection system have made it possible to count $^{10}\text{B}$ groups reliably at energies as low as 500 keV. The low threshold was not crucial to the study of the reaction to the four lowest states of $^{10}\text{B}$, where the cross section can be determined from the alpha particle yield. However, it was important to the study of the 3.59-MeV state, whose alpha particles are obscured by the alpha particles from a $^{12}\text{C}$ target impurity, and to the study of the (presumed) 5.17-MeV (T = 1) state, which cannot be resolved from neighboring particle-unstable states. For the four lowest states, the $^{10}\text{B}$ cross section was determined from the alpha particle yields and checked with the $^{10}\text{B}$ yields; for the other two states it was determined from the $^{10}\text{B}$ yields alone.

Differential cross sections at two angles have been taken in 100 keV steps from near threshold at 5.5 MeV to 18 MeV. Angular distributions have been taken at the following energies (in MeV):

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>5.80</th>
<th>7.40</th>
<th>9.40</th>
<th>12.00</th>
<th>16.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.15</td>
<td>7.95</td>
<td>10.20</td>
<td>13.15</td>
<td>17.00</td>
<td></td>
</tr>
<tr>
<td>6.65</td>
<td>8.40</td>
<td>10.90</td>
<td>14.00</td>
<td>18.00</td>
<td></td>
</tr>
<tr>
<td>7.15</td>
<td>8.70</td>
<td>11.40</td>
<td>15.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Some of these energies correspond to resonances which can be identified with excited states in $^{14}\text{N}$.) At energies where full angular distributions were measured, the total cross section was determined by integration. Total cross sections were found at the remaining energies by interpolation, guided by the measured excitation functions for the differential cross sections (taken at $\theta_L = 30^\circ$ and $40^\circ$ from 5.5 MeV to 10.0 MeV, and at $\theta_L = 40^\circ$ and $90^\circ$ from 10.0 MeV to 18.0 MeV). The cross section for the production of $^{10}\text{B}$ was obtained by summing over the total cross sections for the five bound states and one unbound state (5.17-MeV, T = 1) of $^{10}\text{B}$ (Fig. 7.1-1). No indication is seen for $^{10}\text{B}$ recoils from any other states, up to an excitation energy of 15 MeV.

The $^6\text{Li}$ data is still being analyzed. The analysis is more complicated than for the $^{10}\text{B}$ data, especially because it is necessary to estimate the number of counts lost below the low energy cutoff in the continuous Li spectrum.
Recent developments somewhat alter our perspective concerning the importance of these low energy reactions to light element production. Several theoretical analyses have suggested that $^7$Li can be produced in helium flashes in stellar interiors. These provide an explanation for the observed correlation between high Li and high $^{13}$C stellar abundances, with the Li as $^7$Li, in contrast to our earlier conjecture that the high Li might be in the form of $^6$Li. On the other hand, recent estimates of meteoritic boron abundances have given new plausibility to the suggestion that light element production occurs in significant amounts in low density outer regions of supernovae. In this case, reactions involving ~10 MeV protons, such as those being studied on $^{14}$N and $^{13}$C, assume great importance.

2. See Sec. 3.4 of this report.


6. See Sec. 7.3 of this report.

7.2 Production of $^6$Li and $^{10}$B in Alpha Particle Bombardment of $^{14}$N


Although in most environments where light element production might occur alpha particles are much less numerous than protons, alpha particle reactions may nonetheless play a significant role in the synthesis of the light elements. For example, in the galactic cosmic rays the alpha particle flux is only about 1/10 the proton flux at a given energy (MeV/nucleon). However, the reaction thresholds (MeV/nucleon) are usually lower for incident alpha particles than for protons, and thus alpha induced reactions will be important if the energy spectrum of the incident particles rises steeply at low energies. In addition, for reactions where cosmic ray nuclei of C, N, or O are incident upon interstellar hydrogen or helium, the center-of-mass energy is greater for the case of the helium target, again enhancing the importance of reactions involving alpha particles.

The reactions $^{14}$N($\alpha$,2$\alpha$)$^{10}$B and $^{14}$N($\alpha$,C)$^{6}$Li have particularly low thresholds, with Q values of -11.7 MeV and -8.8 MeV respectively. A measurement of the cross sections for these reactions has begun using a pulsed alpha beam from the Van de Graaff accelerator on thin adenine targets. The reaction products are identified by an on-line time-of-flight system. The total cross section is determined by integrating over the measured angular distribution. Preliminary data have been obtained at 23 and 26 MeV showing substantial yields of $^{10}$B and somewhat lower $^6$Li yields.

7.3 Excitation Functions for $^{14}$N(p,α)$^{11}$C and $^{14}$N(p,2α)$^7$Be


Two possible corrections to these previously reported cross sections were investigated: the effects of multiple scattering on the beam current integration, and the possible loss by gaseous diffusion of $^{11}$C from adenine targets.

During activation of the adenine targets, elastically scattered protons were counted to monitor the product (target thickness)\times(beam flux). Thus, beam current integration was unnecessary during these runs, assuming the elastic differential cross section to be known. This cross section had been measured over the energy range of interest using a $^{14}$N gas target. A re-examination of the gas target measurement indicated that there had been some error in beam integration due to scattering in the gas and in the 0.1-mil Havar windows on the gas cell. The errors were found by further measurement to vary from 1% at 9 MeV to about 5% at 6 MeV, implying corrections of comparable magnitude to the previously quoted
reaction cross sections.

It has been known for some time\(^2\) that a significant amount of the \(^{11}\text{C}\) activity produced during bombardment of polyethylene and polystyrene targets may be lost by escape of radioactive gases (the loss being substantially higher for polyethylene than for polystyrene). A test was made in order to determine whether a similar loss may occur for the adenine targets used to study the \(^{14}\text{N}(\text{p},\alpha)^{11}\text{C}\) reaction. Adenine targets were placed in vacuum-tight evacuated cells and bombarded with the proton beam. The cells (and targets) were then removed from the beam and the annihilation radiation from the positron decay of \(^{11}\text{C}\) was counted in coincidence. After establishing the magnitude and slope of the decay curve, the cell was flushed several times and counting resumed. Any loss of activity from the target would result in a shift of the decay curve. In repeated runs, no shift was observed within a detection sensitivity of 1%. Using the same method, the loss for a 9.5 mg/cm\(^2\) polyethylene target was found to be 4.5%. Previous measurements\(^3\)–\(^5\) for the loss in polyethylene give an average of 13.5%. In the absence of an explanation for our relatively low measured value for the loss in polyethylene, we place an upper limit of 3% on the possible loss of \(^{11}\text{C}\) from adenine targets.


7.4 Electromagnetic De-excitation of Excited States in \(^{12}\text{C}\)


We have measured the branching ratio, \((\text{Frad}/\Gamma)\), for the 7.65-MeV state of \(^{12}\text{C}\) to be \((4.3 \pm 0.4) \times 10^{-4}\). This result is significantly higher than the currently accepted value\(^1\) of \((2.9 \pm 0.3) \times 10^{-4}\), implying that the rate of the stellar triple-alpha process \((3\alpha \rightarrow ^{12}\text{C})\) at a given temperature and alpha particle density is about 50% faster than previously thought.

The techniques used are similar to those reported previously for the similar measurement for the 9.64-MeV state of \(^{12}\text{C}\). The 7.65-MeV state is excited by inelastic alpha particle scattering at an incident alpha particle energy of 24 MeV. Electromagnetic de-excitation is identified as a coincidence between the inelastically scattered alpha particle and the associated \(^{12}\text{C}\) nucleus. The branching ratio is calculated from the ratio of the number of such coincident events to the number of inelastically scattered alpha particles, corrected for the efficiency for \(^{12}\text{C}\) detection and for dead time losses.

Thin transmission mounted silicon surface barrier detectors are used to detect both the alpha particle and the \(^{12}\text{C}\). Events of interest are defined by
the proper particle energies and the proper difference between the flight times for the coincident particles. The time difference is determined by using a time-to-amplitude converter with an overall timing system resolution of about 1 nsec for mono-energetic particles. For each coincidence event, the two energy signals and the timing signal are processed in an on-line computer, giving immediate displays of the most relevant data, and recording each event individually on magnetic tape for subsequent further analysis.

The entire system, including the efficiency for the detection of the recoil $^{12}C$, is checked by coincidence measurements for the $^{12}C$ ground state and 4.43-MeV state, at angles such that the $^{12}C$ recoil energy is the same as that for the 7.65-MeV state. The measured ground and 4.43-MeV state efficiencies are fit by a Monte Carlo efficiency calculation, with a typical agreement within 2%. The Monte Carlo calculation, amended to allow for the additional gamma decay, is then used to predict the efficiency for the 7.65-MeV state. These predicted efficiencies ranged from about 68% to 94%, depending upon the size and distance of the $^{12}C$ detector.

Target contamination difficulties were studied by taking runs under

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**Fig. 7.4-1.** Branching ratio, $\Gamma_{rad}/\Gamma$, for the 7.65-MeV state of $^{12}C$, for differing $^{12}C$ detector diameters, $d_r$.\[60\]
conditions identical to those for data runs, with targets of $^{13}$C and natural N and O. The general background was examined by taking runs with the $^{12}$C detector displaced by a small amount, typically 3° or 4°, from its proper position. It was concluded that target impurities and background made a contribution of less than 8% to the observed events.

Data was taken primarily with the inelastic alpha particle detected at a peak in its differential cross section at 65° (lab). The alpha particle detector was 8" from the target and had a defining aperture 3/8" in diameter. The recoil $^{12}$C were detected in two different detector systems: a detector 3/8" in diameter at distances of 6, 8, and 10 inches from the target, and a detector 3/4" in diameter at distances of 12, 15, and 20 inches. A small amount of data was also taken at a secondary maximum in the alpha particle differential cross section, at 95°.

Results obtained in these different geometries are displayed in Fig. 7.4-1. Overall, the results are consistent with an average branching ratio of $4.3 \times 10^{-4}$. In Fig. 7.4-1, only statistical standard deviations are shown. The systematic uncertainties are larger than the overall statistical uncertainty and lead to the quoted probable error of $0.4 \times 10^{-4}$.

Study of the 9.64-MeV state was deferred pending completion of the work on the 7.65-MeV state and procurement of a target in which the $^{13}$C content is very small. Both have now been accomplished, and measurement of the 9.64-MeV state is resuming.


7.5 Accelerator Production of $^8$B Neutrinos

E.G. Adelberger, D. Bodansky, and R.E. Mars

The negative results obtained to date in the search by Davis for solar neutrinos\(^1\),\(^2\) have led to dramatic suggestions as to possible explanations. These include the suggestion by Bahcall, Cabibbo and Yahil\(^3\) that neutrinos may decay in flight and the suggestion by Fowler\(^4\) that the temperature in the solar interior may have decreased substantially in the past $10^7$ years. An alternative suggestion,\(^5\) that the relevant branching ratios in the nuclear reaction chain are changed by a resonance in $^6$Be, appears to be ruled out by the recent study by Parker\(^6\) of the $^6$Li($^3$He,$^3$H)$^6$Be reaction.

In view of the importance of the problem and the drastic nature of the current suggested explanations, it is worth considering the possibility of making a direct experimental determination of the detection properties of the type of neutrino detector used in the Davis experiment. The expected counting rate for a given flux of neutrinos is based on knowledge of the neutrino energy spectrum, the energy-weighted cross section for the reaction $\nu + ^{37}$Cl $\rightarrow ^{37}$Ar + e, and the efficiency for collecting $^{37}$Ar and detecting its decay. In the absence of a
neutrino source of known flux, it is impossible to subject all these expectations to a complete, direct experimental test. This has not been considered worrisome because theoretical calculations of the neutrino capture rate appear to be very reliable, and checks of the component features of the experimental system are extremely convincing. However, the longer the puzzle exists, the more tempting it is to consider the possibility of a direct check of the neutrino detection efficiency.

To explore one possible neutrino source, we have measured the cross section for the reaction $^6$Li($^3$He, n)$^8$B for incident $^3$He in the energy range from 8.9 to 26.5 MeV (lab). The choice of $^8$B is directly prompted by the predictions of conventional solar models, which attribute the bulk of the anticipated $^7$Ar yield to the neutrinos from the decay of $^8$B. The measurement of the $^6$Li($^3$He, n)$^8$B cross section was performed by bombarding a thick target of enriched $^6$Li metal with a $^3$He beam from the tandem Van de Graaff accelerator. The yield of $^8$B was determined by counting the 511-keV $\gamma$-rays resulting from the 0.762-sec positron decay of $^8$B.

Figure 7.5-1 shows a diagram of the experimental arrangement. The targets were bombarded for about 5 sec and then transported 4 m by a helium driven "rabbit" system to a well-shielded counting location, where the target activity was counted with a Ge(Li) detector situated at a distance of 38 cm from the target. Vacuum windows of 0.1-mil Havar foil were located approximately 1 cm upstream and 1 cm downstream of the bombardment position, and the $^3$He beam was collected in a Faraday cup when it was not blocked by the target. Because the annihilation $\gamma$-rays of interest come from positrons whose energies extend to 14 MeV, it was necessary to surround the target counting position by a lucite cylinder to stop the positrons. The cylinder was 16 cm in diameter, 31 cm long, and had a 2.7 cm diameter hole along the axis for insertion of the rabbit.

The targets were prepared in an argon atmosphere by pressing $^6$Li metal into a small aluminum boat and covering the front surface with a 0.1-mil Havar foil. The targets were about 2.5 mm thick, which was sufficient to stop the $^3$He beam at the highest energies used. After completion of the data collection the cover foil was removed to verify that the $^6$Li surface had remained clean.

The efficiency of the detector for 511-keV $\gamma$-rays was determined by
Fig. 7.5-2. Cross sections for the $^6\text{Li}(^3\text{He},n)^6\text{B}$ reaction. $\bar{\sigma}$ is the measured thick target average cross section; $\sigma$ is extracted from it by successive differences. For $\bar{\sigma}$ the energy scale corresponds to the $^3\text{He}$ lab energy at the front surface of the $^6\text{Li}$. The errors shown are statistical standard derivations; systematic uncertainties are about 10%. The curves are drawn only to guide the eye.

calibration with commercially obtained $^{22}\text{Na}$ sources placed at the target counting position. A correction of 10% was made to account for the difference in the annihilation in flight of positrons from $^8\text{B}$ and $^{22}\text{Na}$. Further corrections of about 1% each were included to account for the finite bombardment time and for the calculated differences in the effective source location for $^{22}\text{Na}$ (short range positrons) and $^8\text{B}$ (long range positrons).

The 511-keV activity was counted during a time interval beginning 0.43 sec after the target left the bombardment position and continuing for 13.6 sec. The counting interval was divided into 10 time bins varying in length from 0.4 to 3.2 sec, and the portion of the $\gamma$-ray spectrum containing the 511-keV activity was recorded separately for each time bin. Least squares fits were made to the decay data. No evidence was found for any activities other than the 0.762-sec activity from $^8\text{B}$ and a slowly varying background which was assigned a nominal half-life of
100 sec for the purpose of analysis.

As a check of our beam current integration system, the monitor reaction $^{27}$Al($^3$He,$^2p$)$^{28}$Al was used to compare the present Faraday cup configuration with another Faraday cup whose accuracy has been better established. This test was done by activating aluminum foils in the rabbit system and in a scattering chamber at a different location. Some difference appeared in the normalized $^{28}$Al yields for the two arrangements. In consequence, a correction was made to the flux in the present arrangement, amounting to increasing the measured flux by 9% at the lowest $^3$He energy and 5% at the highest energy, with a monotonic variation between. It was estimated that the uncertainties in the corrections were approximately equal to the corrections themselves. As the correction and uncertainty were not large at the energies of greatest interest, namely above 20 MeV, no extensive attempts were made to explore the reasons for the discrepancy.

A range-averaged total cross section $\bar{\sigma}$ was obtained from the $^8$B production yields at each energy by treating the $^3$He range in $^6$Li as an effective target thickness. The results are displayed in Fig. 7.5-2, together with the usual cross section $\sigma$, obtained from $\bar{\sigma}$ by successive differences.

The results are displayed in Fig. 7.5-3 in a manner more relevant to the question at hand. The present upper limit on the capture rate in $^{37}$Cl is 1 SNU, corresponding to a flux of $0.74 \times 10^6$ $^8$B solar neutrinos per cm$^2$-sec. In Fig. 7.5-3 we display the $^3$He$^+$ current as a function of $^3$He energy required to produce this flux from the $^6$Li($^3$He,$n$)$^8$B reaction at a distance of 8 m from the target. This distance corresponds to the effective average distance in a hypothetical geometry in which the $^6$Li target is situated 5 m in front of a cylindrical tank which is 5 m in length and in radius. While not necessarily an optimum geometry, this corresponds roughly to the volume of the present Davis tank, and allows room for adequate shielding against neutrons produced in the target. Thus, for example, a 24-MeV $^3$He accelerator producing a $^3$He$^+$ current of 30 mA would be adequate for making the contemplated test.

8. WEAK INTERACTIONS

8.1 Search for a Parity Violating M1 Transition in $^{19}$F

E.G. Adelberger, M.D. Cooper, H.E. Swanson, and J.W. Tape

INTRODUCTION

At present most experimental evidence for the size of parity and mixtures in nuclei comes from circular polarization measurements of gamma-rays from unpolarized heavy nuclei. In these nuclei the complexity of the nuclear physics leads to large uncertainties in the theoretical predictions. A particularly nice measurement exists in $^{16}$O where the parity forbidden $\alpha$ decay of the 8.87 MeV $J^\pi = 2^-$, $T = 0$ has been observed. Here the nuclear physics is quite simple -- the width is due to slight admixtures of several nearby $J^\pi,T = 2^+,0$ levels and arises only from the $\Delta T = 0$ weak nuclear nucleon force. We are studying a case in $^{19}$F where the nuclear physics is again especially simple and which is sensitive to both the $\Delta T = 0$ and $\Delta T = 1$ weak forces. A previous attempt (using quite different experimental techniques) to detect the parity mixing in $^{19}$F was not sufficiently sensitive.

THE NUCLEAR PHYSICS

As was first pointed out by Maqueda, the ground and 110 keV excited states of $^{19}$F ($J^\pi = 1/2^+$ and $1/2^-$ respectively) form an excellent case to study parity mixing since the situation should be well approximated by simple two-state mixing. (The next $J = 1/2$ state in $^{19}$F occurs at an excitation energy of 5.34 MeV. Thus we can write

$$|g.s.\rangle = |+\rangle - \epsilon |-\rangle$$

$$|110\rangle = |\rangle + \epsilon |+\rangle$$

$$\epsilon = \frac{\langle |H_{\text{weak}}|+\rangle}{110 \text{ keV}}.$$

The EM matrix element connecting the states is then

$$\langle g.s.|E1 + M1|110\rangle = \langle +|E1|-\rangle + \epsilon [\langle -|M1|-\rangle - \langle +|M1|+\rangle] + \theta(\epsilon^2)$$

where we have ignored parity violating exchange contributions. In this case the parity violating M1 transition can be calculated exactly from the magnetic moments of the two levels and $\epsilon$. The M1/E1 parity violating mixing ratio can be determined by measuring the anisotropy $(1 + P\cos \theta)$ of the 110 keV de-excitation radiation from a polarized ensemble of $^{19}$F's. ($P$ is the average polarization of the $^{19}$F's; $\delta$ is proportional to $\epsilon$ and involves the magnetic moments and the E1 lifetime.) Maqueda has calculated $|\delta|$ to be $4.3 \times 10^{-4}$ using Michel's parity violating potential.

EXPERIMENTAL DESIGN

The $^{19}$F's are polarized by producing them in the reaction $^{22}$Ne(p,α)$^{19}$F with
a polarized proton beam at an incident energy of 4.96 MeV. The spin structure of this reaction is $0^+ + 1/2^+ \rightarrow 0^+ + 1/2^-$ and large polarization transfers are expected, even if one averages over all $\alpha$-angles and employs a very thick target. For example, if the outgoing $\alpha$'s are s-wave the polarization transfer is $-1$ ($^{15}$F spin opposite to proton spin). The polarization is retained for a time $\tau$ the 880 ps lifetime of the 110 keV level by choosing the target gas pressure so that the recoiling $^{15}$F's decay before they come to rest. In this fashion the rapidly fluctuating magnetic fields which occur during slowing down do not cause any net procession of the moment. The beam is polarized left or right and gamma rays are detected in two $10 \text{ cm}^2 \times 7 \text{ mm}$ planar Ge(Li) detectors mounted on the left and right sides of the gas cell (see Fig. 8.1-1). The experiment is designed to have

![Diagram of geometric setup](image)

**Fig. 8.1-1.** Geometry of the parity mixing experiment. The He gas cell and proton counters are used to measure the beam polarization.

a sensitivity of $\sim 10^{-5}$. Hence we need $10^{10}$ counts and careful procedures to remove systematic errors. With a beam current of 25 nA, the required counts can be obtained in $\sim 5$ days of running time in the present geometry. The procedures to reduce systemic errors will be discussed below.

**HARDWARE**

An extension to the $45^\circ$ beam line was constructed to handle this experiment. A gas cell having extremely low mass (.010" Al wall thickness, for example) and good symmetry properties was designed and constructed. The cell was designed so that both counters view the entire interaction volume. The quality of the gamma ray spectra, in particular the virtual absence of undesired radiation such as x-rays (obtained by constructing the entire cell and collimators from low Z materials), of radiation compton scattered in matter surrounding the cell and the excellent peak to background ratio in the region of interest (see Fig. 8.1-2) attests to the success of the design of the cell and counters.

Extensive modifications to the polarized ion source were needed to obtain the fast periodic spin flip. Work in this area is continuing both to increase
Fig. 8.1-2. Spectrum of gamma rays observed in the thin window planar Ge(Li) detectors. Note the excellent peak-to-valley ratio of the 74-keV and 110-keV peaks. Approximately 1/2 of all events in the Ge(Li) detectors lie in the 74 and 110-keV photopeaks.

the output of the polarized source and to remove residual steering effects when the spin is flipped. Two fast (dead time/event ≈ 10 μsec) pulse height analyzers are being pur chased and will be employed to digitize the gamma ray spectra.

MEASUREMENT OF THE AVERAGE $^{19}_F\pi$ POLARIZATION

The anisotropy of the 110 keV radiation is proportional to the net polarization of the $^{19}_F\pi$'s averaged over the lifetime of the level. We determine the net polarization by measuring the circular polarization of the 110 keV radiation. Those 110 keV photons which propagate along or against the quantization axis of the magnetic substates will have a circular polarization equal to the linear polarization of the $^{19}_F\pi$'s (see Fig. 8.1-3). The circular polarization is measured using the spin dependence of the Compton scattering cross section with a transmission magnet. At 110 keV the analyzing efficiency of the transmission magnet is roughly $3 \times 10^{-3}$. The

Fig. 8.1-3. Magnetic substates involved in the 110 keV radiation. A photon emitted along the quantization axis will have a circular polarization equal to the linear polarization of the $^{19}_F\pi$. 
transmission magnet has a projected thickness to the gamma rays of 0.8 cm and a symmetric design so that the magnetic field at the center (the beam position) is very small. The magnet was driven to saturation with the magnetization direction reversed every second. The outputs from the two Ge(Li) counters were then routed into different sections of the computer memory according to the polarization state of the beam. The polarization state of the beam was reversed between each of the four runs and the asymmetry coefficient \( A = (R^+ / R^-)(L^- / L^+) = 1 + 4f \) computed for each run, where \( R \) and \( L \) denote counting rates in the right and left counters, + and - refer to the magnetization projection pointing toward or away from the beam respectively and \( f \) is the product of the circular polarization analyzing efficiency times the circular polarization of the 110 keV radiation. In the ideal case the sign of \( f \) would change when the beam polarization is changed. We observed that \((A - 1)\) with beam polarized left was not equal to \((1 - A)\) with the beam polarized right. This is presumably due to slight misalignments which can produce a weak magnetic field at the beam position and steer the beam so as to produce a false asymmetry. However, when one reverses the proton spin the steering effects (and hence the false asymmetry) are unchanged while the true asymmetry (due to the spin dependent Compton cross section) changes sign. Thus the difference in asymmetries with spins left and right gives the true asymmetry. A preliminary analysis indicates that the \( 19F \) polarization = \((-0.75 \pm 0.25) \times \text{beam polarization} \) where the error is at the moment dominated by uncertainties in the analyzing efficiency of the transmission magnet. This is quite satisfactory for our purposes.

**MEASUREMENT OF THE ASYMMETRY DUE TO PARITY VIOLATING M1/E1 MIXING**

For this measurement the transmission magnet is removed, the proton spin is flipped repetitively and the counters placed 5 cm from the beam. We measure a quantity \( A_P = (R^+ / R^-)(L^- / L^+) = 1 + 4P\delta \) where \( P \) and \( \delta \) are defined above. Note that the polarization states (+) and the counters \( R \) and \( L \) appear in both the numerator and denominator causing many systematic effects to cancel. An effect which would not cancel, however, would be a correlation between the beam position and the polarization state. This and other such sources of false asymmetries are removed by picking a bombarding energy such that in addition to the 110 keV radiation from \(^{22}\text{Ne}(p, \alpha)^{15}\text{F}\) we also produce 74 keV radiation from the \(^{22}\text{Ne}(p, n)^{23}\text{Na}\) reaction (see Fig. 8.1-2). The 74 keV gamma ray comes from the de-excitation of a \( J = 0 \) level and hence is rigorously isotropic. By taking the ratio of 110 to 74 keV gammas one can very accurately correct for beam motion, higher order dead time effects, etc. Since about half of all events in the Ge(Li) detectors lie in the 110 keV and 74 keV photopeaks very high counting rates of these peaks can be tolerated.

Preliminary results with poor statistics, using the computer's ADC's instead of the fast analyzers and old poor resolution Ge(Li) detectors give an asymmetry of \(|\delta| = (4.5 \pm 3.3) \times 10^{-4}\) which is not significant.

At present work on this experiment is concentrated on improvements to the ion source.
9. REACTIONS AND SCATTERING (A > 16)

9.1 Highly Inelastic Deuteron Scattering


Measurements of highly inelastic deuteron scattering from targets ranging in mass from A = 60 to 120 have been made using 22 MeV deuterons from the tandem accelerator. These measurements were initiated to further explore several interesting phenomena and questions raised by the observations of G. Chenevert on inelastic $^3$He and $\alpha$ scattering.

**Gross Structure in Highly Inelastic Scattering Spectra**

The first phenomenon, a broad structure in the $^3$He and $\alpha$ spectra at forward scattering angles in the excitation energy range 8 to 30 MeV has already received some attention at this laboratory. Brown et al. have shown that a portion of the observed structure in the ($\alpha,\alpha'$) spectra is associated with the breakup of $^5$He particles resulting from the pickup of neutrons by the incident $\alpha$ particles. When this $^5$He part of the ($\alpha,\alpha'$) spectrum is subtracted from the rest of the spectrum a peak remains near 8 MeV excitation which is similar to the structure seen in the ($^3$He,$^3$He') spectra. It has been suggested by Chenevert, Lewis and others that collective multipole resonances may be responsible for this structure.

Unfortunately it has not so far been possible to find experimental signatures which can isolate and unambiguously assign multipolarities to these higher lying spectral structures. It was decided to pursue the problem further by seeing whether structures corresponding to those seen by Chenevert also appear in ($d,d'$) spectra. The familiar lower lying collective $^3$ and $2^+$ resonances, for example, have been seen by many groups to appear in ($p,p'$), ($d,d'$) and ($\alpha,\alpha'$) spectra.

We have measured the inelastic cross section of 22 MeV deuterons on $^{66}$Zn, $^{89}$Y, $^{92}$Mo, $^{102}$Pd, $^{112}$Ag, and $^{120}$Sn from 35° to 135°. Particle identification was accomplished using a 3 detector telescope which had an energy range for deuterons from 3.5 MeV to more than 22 MeV. The data were recorded event by event on magnetic tape using an on-line computer. Background from carbon and oxygen contamination of the targets was removed by taking carbon and oxygen spectra at each angle for subtraction. The solid angle defining aperture for the telescope was placed between the first and second transmission detectors so that background due to scatterings of the elastic part of the spectrum from the aperture edge could be identified and removed by comparing the signals of the first two detectors. This method is not, however, 100% effective and the very large, elastic cross sections at small angles have so far prevented accurate measurements forward of 35°.

It is not yet clear whether there is any correspondence between structure seen in the $d,d'$ spectra and the structure seen by Chenevert with $^4$He and $^3$He particles. A structure reminiscent of those seen by Chenevert in heavy nuclei at 8 to 10 MeV is seen in $^{102}$Pd($d,d'$) at 5.5 MeV (see Fig. 9.1-1). This peak lies too low in excitation, however, to be associated with any collective multipole
Fig. 9.1-1. $^{102}$Pd(d,d') energy spectrum at 45° with an incident energy of 22.0 MeV, which might be responsible for the peak in heavier nuclei at 8-10 MeV since collective excitation energies are expected to decrease as A increases going roughly as $A^{-1/3}$.

If higher lying structures in (p,p'), ($\alpha$,α') and ($^3$He,$^3$He') spectra are not also found in (d,d') spectra, one may speculate that the weakly bound deuteron tends to break up more readily in encounters which involve large energy transfers than do the other projectiles.

Dependence of Total Inelastic Scattering Cross-Sections on A

A second feature of the $^3$He work which we wanted to investigate, the A dependence of the total inelastic scattering, had not before received much attention. In the limited mass region studied by Chenevert ($A = 181$ to $A = 208$), the total $\alpha$ inelastic cross section appeared to vary as $A^{5/2}$. This is a much stronger variation with A than would be expected from any simple model for scattering. For an incident particle which is only weakly absorbed in the nucleus, one would expect a cross-section proportional to A. For particles with mean free
paths of the order of the nuclear radius or smaller, the strongly shadowed nu-
cleons become ineffective scatterers and the total scattering should therefore go
more weakly than $A$. That is, if the cross-section goes as $\propto A^n$, we expect $n < 1$.

Figure 9.1-2 shows how the energy-integrated inelastic (d,d') differential
cross-sections at 35° depend on $A$. (The angular distributions for the different
targets are sufficiently similar that the 35° cross-sections can be taken as
roughly proportional to the angle-integrated cross-sections.) The $A$ dependence
is seen to be fairly complicated for data in the excitation region, 0.2-5 MeV
(mainly the $2^+$ and $3^+$ excitations), but somewhat less so in the 5-10 MeV and 10-
15 MeV excitation region. The 5-10 and 10-15 cross-sections (with the exception
of that for $^{66}$Zn) are found to go roughly as $A^{1.75}$. However, the large cross-
section for $^{66}$Zn makes it seem unlikely that there is a smooth $A$ dependence (and
a simple explanation for it) for the total (d,d') cross-section. This is to be
contrasted with the recent measurements with 62 MeV protons$^4$ where it has been
found that the $A$ dependence of the integrated (p,p') cross-section minus the
evaporation component varies smoothly with $A$ for all but the lightest targets,
going very nearly as $A^{1/3}$. The evaporation component was subtracted from the
total \((p,p')\) cross-section because it is large (sometimes greater than 50% of the total) and varies strongly as a function of proton binding energy, thereby masking the \(A\) dependence of the remaining inelastic cross-section. This is not important for the alphas and deuterons where evaporation accounts for less than 10% of the total inelastic cross-section. At this point the \((d,d')\), \((p,p')\), and \((a,a')\) results all seem to be different from each other with regard to the question of \(A\) dependence. They are also different in magnitude. For a medium weight nucleus \((A \approx 100)\) the integrated \((p,p')\) cross-section, minus the evaporation component, with 62 MeV protons is \(420 \pm 40\) mb.\(^4\) The \((a,a')\) integrated cross-section with 65 MeV \(a\) particles is \(270 \pm 30\) mb for Ta.\(^1\) It is not known for lighter targets. In contrast to these large values the \((d,d')\) integrated cross-section for \(A \approx 100\) seems to be only \(\approx 70\) mb. The uncertainty on this estimate is about 30%. It arises from the lack of data at the most forward angles which was mentioned above. It is clearly desirable to acquire better data at forward angles and to extend the \((d,d')\) work to deuteron energies more nearly comparable to those used in the proton and \(a\) particle investigations.

Search for Evidence of Multiple Scatterings within the Nucleus

The large values of the \((a,a')\) and \((p,p')\) total inelastic cross-sections suggest that the ratio of the probabilities for scattering in the nucleus is not too small compared to that for the destruction of the projectile (by absorption into the compound nucleus, by conversion to another particle by pickup, etc.). Under the circumstances, the probability for two or more scatterings during passage through the nucleus should be sizable. Although there is little evidence for such multi-step processes in excitations of low-lying nuclear levels, one would expect ever greater contributions of multiple interactions as the residual excitation increases. To know how much multiple-scattering occurs and what the spectrum of such events looks like is important for the interpretations of structures one sees in the higher lying inelastic scattering excitations. The multiple events provide a background which must be subtracted. So far the subtractions made in trying to identify collective modes at high excitations have generally been very questionable.

In almost any reasonable model, the relative contribution of multiple-event scattering should be larger at higher excitation energies. It is also true that the probability for say three-fold events should increase more rapidly with nuclear size (i.e., with \(A\)) than that for single or for two-fold events. Thus it suggests itself that the different portions of the inelastic spectrum would have a different \(A\) dependence -- the greatest inelasticities showing the strongest \(A\) dependence. A very preliminary examination of our deuteron data as well as a rough examination of Chevret's data on helions does not show such a systematic change of \(A\) dependence of the various portions of the inelastic spectra. We intend to pursue this problem further.

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4. F.E. Bertrand and R.W. Peelle, private communication.
9.2 Study of the Quasi-Elastic \( (p,n_A) \) Reaction

M.P. Baker, M. Hasinoff\textsuperscript{2}, D.L. Johnson, and H. Wieman

The quasi-elastic \( (p,n_A) \) reaction is normally analyzed as a direct reaction which proceeds via the \( T^* \) term in the nucleon-nucleus optical potential. The analog neutron group is normally observed as a sharp peak sitting on a smooth background in a time-of-flight or neutron energy spectrum and the contribution of the compound nuclear process is taken into account by subtracting a smooth background beneath the peak. However, consideration of the various isospin amplitudes involved in the compound nuclear process shows that this procedure accounts only for the decay of the \( T_2 \) compound nuclear states to the \( T_2 \) levels in the residual nucleus. The \( T_2 \) states in the residual nucleus, which correspond to the analog neutron groups, in addition to being populated via a direct reaction, can also be populated by neutron emission from either \( T_2 \) or \( T_2 \) compound nuclear states.

In the present experiment we have studied the \( ^{48}\text{Ca}(p,n_A)^{48}\text{Sc}(\text{IAS}) \) reaction from \( E_p = 8.1 - 17.0 \text{ MeV} \) to determine the relative contributions of the direct and compound nuclear reaction amplitudes. Earlier measurements reported last year\textsuperscript{1} showed resonant structure in the \( ^{89}\text{Y}(p,n_A)^{89}\text{Zr}(\text{IAS}) \) yield curve but the interpretation of these results in terms of a \( T_2 \) compound nuclear resonance was complicated by the fact that the resonance was located less than 1.5 MeV above threshold in the region of the celebrated zero energy p-wave neutron "size" resonance of the mass 90 region. Attempts to determine the location and magnitude of the p-wave "size" resonance in neighboring nuclei were unsuccessful because of the low cross section for the analog neutron group. The present \( ^{48}\text{Ca}(p,n_A)^{48}\text{Sc} \) (IAS) measurements covered the energy region \( E_p = 8.1 - 17.0 \text{ MeV} \) \( (E_n = 1.0 - 9.0 \text{ MeV}) \), most of which is far from threshold.

The experimental arrangement was identical to that used in the previous measurements.\textsuperscript{1} Figure 9.2-1 shows the neutron time-of-flight spectrum at \( \theta_n = 142^\circ \) and \( E_p = 13.1 \text{ MeV} \). The sharp peak in channel 347 corresponds to the lowest \( T_2 \) state in \( ^{48}\text{Sc} \) while the peaks in channels 290, 257 and 246 correspond to excited \( T_2 \) levels in \( ^{48}\text{Sc} \).

The yield curve for the quasi-elastic neutron group leading to the lowest \( T_2 \) level in \( ^{48}\text{Sc} \) was obtained by drawing a smooth curve underneath the peak and integrating the counts in the peak. The \( ^{48}\text{Ca}(p,n_A) \) yield curve at \( \theta_n = 142^\circ \) is compared to the \( ^{48}\text{Ca}(p,Y_0) \) yield curve at \( \theta_Y = 105^\circ \) in Fig. 9.2-2. The \( (p,n_A) \) yield curve contains much structure indicating a large non-direct reaction amplitude. Similar structure was also observed in a 20° yield curve. Most of the peaks correspond to those seen in the \( (p,Y_0) \) reaction as shown by the vertical lines in Fig. 9.2-2. Averaging over the fine structure of width 150-200 keV, the \( (p,Y) \) yield curve shows broad peaks at \( E_p = 9.7, 11.7 \) and 13.4 while the \( (p,Y_0) \) curve shows peaks at \( \sim 9.7 \) and 13.3 MeV with no strong peak at 11.7 MeV. The absence of a strong \( (p,n_A) \) peak in the \( (p,Y_0) \) curve is not too surprising since the capture reaction selectively excites only those states having large electric dipole transition strength to the \( 7/2^+ \) ground state of \( ^{43}\text{Sc} \), i.e., states with \( J^\pi = 5/2^+ \) and 9/2\textsuperscript{+}. 

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Fig. 9.2-1. Neutron time of flight spectrum from the reaction $^{48}\text{Ca}(p,n)^{48}\text{Sc}$ measured at $\theta_L = 142^\circ$. The peaks labeled $n_{A0}$, $n_{A1}$, etc. correspond to neutrons leading to the lowest analog levels in $^{48}\text{Sc}$.

Several neutron angular distributions have also been measured. Attempts to fit the 9.0 MeV angular distribution as a direct reaction using the DWBA program DWJCK are shown in Fig. 9.2-3. The global set of optical model parameters obtained by Bechetti and Greenless predicts a cross section which is more than an order of magnitude too small. Following a suggestion by Miller and Garvey we have performed other DWBA calculations using much smaller values for the absorptive part of the optical potential for the low energy analog neutrons ($W_n = 17.46$ and 8.0 MeV). However, even these calculations are much smaller than the experimental data and they lack the symmetry about 90°. At slightly higher energies ($E_p = 13.1$ MeV) the direct reaction DWBA calculations give magnitudes which are more in agreement with the data but the predicted angular distributions are in disagreement with the experimental results (see Fig. 9.2-4).

Thus it seems that at low bombarding energies ($E_p \leq 14$ MeV) the non-direct or compound nuclear process makes a significant contribution to the quasi-elastic $(p,n_A)$ reaction.
Fig. 9.2-2. Comparison of the $^{48}\text{Ca}(p,n_A)$ yield at $142^\circ$ obtained in the present experiment with the $^{48}\text{Ca}(p,\gamma)$ data of Ref. 5. The vertical arrows show the correspondence in the resonant structure.
Fig. 9.2-3. Angular distribution of the ground state analog neutron group at $E_p = 9.0$ MeV. The curves are DWBA direct reaction predictions using different values for the neutron absorptive potential as proposed by Becchetti and Greenlees$^3$ or Miller and Garvey.$^4$

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1. Department of Physics, University of British Columbia.
3. P.D. Kunz, private communication.
9.3 Relative Neutron and Proton Distributions of $^{48}\text{Ca}$ as Deduced from the Elastic Scattering of Alpha Particles from $^{40},^{48}\text{Ca}$

J.S. Blair, K. Ebisawa, and W.Q. Sumner

A problem which continues to attract much attention is the possible existence of a neutron halo in nuclei with $N > Z$. Previous elastic α-particle scattering experiments carried out at this Laboratory indicated that, for a variety of "strong absorption" radii, the size of $^{48}\text{Ca}$ did exceed that of $^{40}\text{Ca}$ but that the increase was about half the value estimated through use of the average A-dependence of nuclear radii; since elastic electron scattering experiments have shown that the charge radii for $^{48}\text{Ca}$ and $^{40}\text{Ca}$ are nearly the same, it is natural to attribute this increase to the excess neutrons of $^{48}\text{Ca}$.

We have re-investigated this problem, first by re-measuring the elastic scattering from these two isotopes with improved experimental procedures, and second, by relating the deduced phenomenological optical potentials to the underlying nuclear matter densities.

The main experimental improvement derived from use of a transmission-mounted, position-sensitive detector. This enabled us to obtain angular distributions in the range from $18\degree$ to $45\degree$ which contained about 85 equally spaced points. The detector covered about two degrees and at each setting both $^{40}\text{Ca}$ and $^{48}\text{Ca}$ were examined. The angular calibration of the system had been checked and was found accurate to $\pm 0.1\degree$. The angular distributions from the two isotopes are very similar but are offset in angle. In the main, they agree with those of Ref. 1.

Optical model fits using several different parameter sets give equally good results. A well-determined quantity, however, is the real potential in the tail region near the strong absorption radius.

We next assumed that the value at this potential (and to a lesser extent the slope) near 1.5 MeV could be related to the nucleon point densities, $\rho$, through folding with an ad hoc effective alpha-nucleon interaction, $V_{\alpha\alpha}$:

$$V(\mathbf{r}) = \int_{\mathbb{R}^3} v_{\alpha\alpha}( \mathbf{r} - \mathbf{r}' ) \rho(\mathbf{r}') d\mathbf{r}' .$$

The ingredients in the above formula are determined in the following fashion: Electron scattering gives proton charge densities which in turn must have the proton form factor removed to give proton point densities. A fast and efficient program using the Fast Fourier Transform allowed this to be easily done. Assuming the same point densities for $^{40}\text{Ca}$ protons and neutrons, we proceeded to ask what effective interaction is necessary to reproduce the real potential for $^{40}\text{Ca}$. It was found that Woods-Saxon and Gaussian forms for the effective alpha-nucleon interaction gave equivalent results, the specific form of the Gaussian interaction being $275$ MeV $\exp(-(0.7 F^{-1} r)^2)$.

Proceeding to $^{48}\text{Ca}$, we again obtained the proton point distribution from the electron scattering results. Using this density and the effective interaction calibrated by the $^{40}\text{Ca}$ experiment, we then determined the neutron density necessary
to reproduce the real optical potential for $^{48}$Ca. Our densities are compared in Fig. 9.3-1 to those of Hartree-Fock calculations$^6$-$^8$ and a shell model calculation.$^3$ The degree of agreement in this case has encouraged us to analyze in a similar fashion our large store of data for elastic scattering from other nuclei and to refine our calculational procedures.

5. R. D. Martin, private communication.

![CALCULUM DENSITIES](image)

**Fig. 9.3-1.** Calcium Densities. Solid lines are this experiment.

- $\Delta$ Shell Model (Ref. 3).
- $\bigcirc$ Hartree-Fock (Ref. 7).
- $\box$ DDHF (Refs. 6 and 8).

### 9.4 Neutron Pickup Using the $^{208}$Pb($\alpha$, $^5$He) Reaction


Last year we reported the large bump in the forward angle inelastic spectra of high energy $\alpha$ particles scattered from heavy targets$^1$ had been shown to have a large contribution from the ($\alpha$, $^5$He) + ($\alpha$, $^5$n) reaction.$^2$ In those and later experiments the $\alpha$ particle and neutron from the breakup of $^9$He were detected in coincidence and using the kinematics of the breakup process, the differential cross section for the reaction was deduced.$^2$,$^3$ The results of those measurements are summarized in Table 9.4-1.

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The large cross section for this reaction has motivated us to pursue ways in which this unique pickup reaction to an unbound, $l = 1$, state can be used to study details of the pickup process. Here we give the results of an experiment designed to study which final states in $^{207}\text{Pb}$ are populated by the $^{208}\text{Pb}(\alpha, ^5\text{He})$ reaction.

Several days were required to accumulate a typical spectrum using a 10-15 na beam of 42 MeV $^4\text{He}$ ions from our cyclotron. The coaligned counter setup described in Ref. 2 was used to measure neutron- $\alpha$-particle coincidences from $^5\text{He}$'s which break up parallel or anti-parallel to their line of flight. However for these present measurements the neutron counter$^4$ was positioned 140 cm from the target to maximize our TOF resolution without getting interference from the gamma flashes of the next beam burst.

The results of measurements taken with the counters at 45° to the beam are shown in Fig. 9.4-1. The data are displayed in a two-dimensional array of $\alpha$-particle energy, $E_\alpha$, vs neutron energy, $E_n$. The neutron energy was derived from TOF information with a time resolution of 2.8 nsec FWHM. The $\alpha$-particle energy resolution was 700 keV FWHM. Events in which the $^3\text{He}$, emitted at 45° in the lab, leaves the $^{207}\text{Pb}$ in particular excited states lie on different loci $E_\alpha + E_n =$ constant. These curves are also plotted in Fig. 9.4-1. The darkened numbers indicate the largest yields on lines perpendicular to the $E_\alpha + E_n =$ const. loci. Most of the darkened numbers fall in two islands both of which lie on the locus corresponding to pickup of a $3p$ $3/2$ neutron from $^{208}\text{Pb}$. The two islands are those expected from the kinematics of $^3\text{He}$ breakup parallel and anti-parallel to its line of flight.$^{2,3}$ The background is mainly due to random gamma rays which largely disappear when pulse shape discrimination (PSD) is used to distinguish the neutrons from the gamma rays. We found however that PSD gating greatly complicated the determination of our neutron counting efficiency and so it is not used in actual data taking. The enhanced yield just above the $h_2/2$ locus at low $E_\alpha$ is assumed to be due to scattering of higher energy neutrons in the neutron detector shield.

In order to determine the approximate yield to final states in $^{207}\text{Pb}$ from our data (see Fig. 9.4-1), we projected each data point onto the final state loci using a triangular resolution function for $E_\alpha + E_n$ which roughly approximated our experimental resolution. Two projections were made -- one using all the data points and the other only data points with $E_n \leq 5.0$ MeV. Figure 9.4-1 shows the loci are more separated in this low neutron energy region; however these two projections gave no great differences in the results. We find that the $(\alpha, ^3\text{He})$ reaction at this energy favors pickup from the low angular momentum states. Pickup

<table>
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<th>$30^\circ$</th>
<th>$45^\circ$</th>
</tr>
</thead>
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<tr>
<td>$\frac{d\sigma}{d\Omega}$</td>
<td>$45\pm4 \text{ mb sr}$</td>
<td>$15\pm2 \text{ mb sr}$</td>
</tr>
</tbody>
</table>

Estimated Total Cross Section

$^5\text{He}$ tot. $> 69 \text{ mb}$

Table 9.4-1

SUMMARY OF RESULTS

$^{208}\text{Pb}(\alpha, ^5\text{He})^{207}\text{Pb}$ at 42 MeV
Fig. 9.4-1. Yield from $^{208}\text{Pb}(\alpha,^5\text{He}) \rightarrow (\alpha,\alpha'n)$ plotted in a two dimensional array $E_\alpha$ vs $E_n$. The loci $E_\alpha + E_n = \text{const.}$ correspond to the reaction leaving the $^{207}\text{Pb}$ in different excited states. The darkened numbers indicate the largest yield on lines perpendicular to the loci.
from the $3p_3/2$ state has the greatest yield, which is about twice that of the $3p_1/2$ state. The remaining states, except for the $1h_9/2$ have yields between $1/2$ and $3/4$ times the yield to the $3p_3/2$ state; the $1h_9/2$ has only a small yield relative to these other states.

Since the low-lying states in $^{207}$Pb are known to be good shell model states, their spectroscopic factors should be about equal to $2J + 1$. Thus although the yields to the various states are within about a factor of 2 of each other, the lower angular momentum states are favored. The ratio of the yields to the two $3p$ states is probably just a reflection of the $2J + 1$ spectroscopic factor. We are planning to do finite range DWBA calculations using a quasi-bound state form factor for the $^5$He ground state to see if we can get agreement with these results.

Last year when we outlined the kinematic features of the $^5$He breakup we neglected the effect of the Coulomb field of the residual nucleus. We have since estimated that 50% of the $^5$He produced by $42$ MeV $^4$He bombardment of $^{208}$Pb breakup within $25$ fm of the residual nucleus where the Coulomb field is quite strong. The $^5$He's which break up early in this high Coulomb field region have part of their asymptotic kinetic energy tied up in Coulomb potential energy. Since the $\alpha$ particle gets all of this Coulomb energy subsequent to breakup, there is a systematic shifting of our data to $\alpha$ particle energies higher than those expected from $^5$He breakups which occur far from the residual nucleus. Also, since the Coulomb field steers only the $\alpha$ particle after breakup, it also distorts the angular correlation between the $\alpha$ particle and neutron. These Coulomb effects are lessened at higher bombarding energies; we are therefore planning to continue our investigations of this reaction with the 90 MeV $^4$He ion beam from the Berkeley 88" cyclotron in collaboration with Dr. D.L. Hendrie.

10. REACTIONS PRODUCED BY POLARIZED PROTON BEAMS

10.1 Elastic Scattering of Polarized Protons from $^{208}_{\text{Pb}}$


The isobaric analogs of the low-lying states of $^{209}_{\text{Pb}}$, seen as resonances in elastic and inelastic scattering of protons from $^{208}_{\text{Pb}}$, have been shown to involve relatively simple configurations. $^{1,2}$ This has lead to interest in making precise comparisons between experimental and theoretical values of the elastic partial widths of these states. Such comparisons provide information on the extent to which the shell model can reliably predict the details of nuclear structure in this region. It has been difficult, however, to extract unique values for the elastic partial widths from the available differential cross section data because the total widths of these resonances are approximately the same as the spacings between them. This has resulted in a large variety of extracted partial widths with large uncertainties. These ambiguities can, in principle, be resolved by measurement of the analyzing power in the vicinity of these resonances. This follows since the analyzing power is formed from a combination of $S$-matrix elements which is independent of the combination forming the differential cross section.

We have, therefore, simultaneously measured analyzing power and differential cross section excitation functions for elastic proton scattering from $^{208}_{\text{Pb}}$ over the energy region in which the low-lying analog resonances are observed. We have, further, obtained data for inelastic scattering to the 2.613 MeV, $3^-$ excited state of $^{208}_{\text{Pb}}$ over a portion of this energy region.

A schematic view of the target chamber set-up for this experiment is shown in Fig. 10.1-1. Left-right asymmetries produced by the polarized proton beam scattering from an isotopic $^{208}_{\text{Pb}}$ target were measured at scattering angles of $135^\circ$, $150^\circ$, and $165^\circ$ using Si(Li) detectors with acceptance angles of $\pm 2^\circ$. The polarization of the beam was continuously monitored by measuring left-right asymmetries of protons scattered from $^4_{\text{He}}$ at $112^\circ$ where the analyzing power is within a few percent of 100%. To reduce instrumental corrections, the asymmetries were measured twice at each energy, once with the beam spin up and once with spin down.

Figure 10.1-2 shows a schematic energy level diagram for the mass $A = 209$ system. On the right the low-lying states of $^{209}_{\text{Pb}}$ are illustrated. In the middle are their isobaric analogs labeled with the laboratory proton bombarding energies necessary to reach them. The previous elastic scattering results have revealed the presence of 6 even-parity resonances. $^2$ There is one odd-parity state, the $j_{15}/2$, which has analyzing power measurements.
Fig. 10.1-2. Schematic energy level diagram for the mass $A = 209$ system as well as $^{208}\text{Pb}$.

Fig. 10.1-3. Analyzing power and differential cross section excitation functions for proton elastic scattering from Pb at $135^\circ$, $150^\circ$ and $165^\circ$ in the range $14$ - $18$ MeV.

been observed in inelastic scattering but its presence in elastic scattering is not clearly established. Note that the spacings are about 400 keV between states while the measured widths are roughly 250 keV.

The excitation functions obtained for the elastic scattering are shown in Fig. 10.1-3. The target
thickness was 15 – 20 keV and the data were obtained in either 25 or 50 keV steps. The statistical uncertainties are 2% or less. The results of previous measurements of the analyzing power at 135° and 150° are shown for comparison. Structure due to all 6 resonances is clearly seen, particularly in the analyzing power excitation functions. For example, the presence of the 1-wave resonance near 15.7 MeV is obvious in the analyzing power data at 155° but is virtually unrecognizable in the cross section data.

We have begun the analysis of the elastic scattering data by parameterizing the potential scattering background and extracting the resonance parameters by a $\chi^2$ minimization fitting procedure. In this search procedure, the resonance energies and total widths were initially held fixed since they have been reasonably well-established in inelastic scattering studies where the background is lower and only one resonance is usually strongly excited for a given final state. Then the other resonance parameters and the background parameters were simultaneously varied to minimize $\chi^2$. $\chi^2$ was defined in a manner which allowed the differential cross section and the product of analyzing power and differential cross section to be fit simultaneously.

The results of such a fitting procedure are shown at the bottom of Fig. 10.1-3 along with the 165° data. The boxes just above the analyzing power excitation function demonstrate the resonance parameter information which has been obtained. The lines show the resonance energies and the widths of the boxes are equal to the total widths of the resonances. The elastic proton partial widths are proportional to the heights of the boxes. The solid line is the parameterized fit. The $j_{15/2}$ resonance has not yet been included in the analysis.

The dotted line in Fig. 10.1-3 shows the results of a preliminary calculation that describes the background potential scattering with the optical model. The resonance parameters used here were those obtained by Wharton et al. from previous measurements of the elastic scattering differential cross section. The optical model parameters were taken from the Becchetti-Greenless global fits for $A > 40$, $E < 50$ MeV. We anticipate that optical model parameters more appropriate to 208Pb will yield a better fit to the data.

The proton elastic partial widths obtained with our parameterized background fitting procedure are given in Table 1 along with results obtained in other analyses. The partial widths quoted for the present analysis are averages of values extracted at each of the three scattering angles; the uncertainties quoted are the rms deviations calculated from the three sets of values.

Inelastic scattering data were also collected simultaneously with the elastic scattering data. Differential cross sections and analyzing powers have only been calculated for those data in the energy region near the overlapping $87/2 - d3/2$ doublet, where it was felt that these quantities might ultimately be useful in studying this doublet. Figure 10.1-4 shows the preliminary excitation functions for scattering to the highly collective 3+ state in 208Pb. Structure in the vicinity of 17.4 MeV is clearly seen. Interpretation of this structure is difficult because potentially there are several mechanisms which
Fig. 10.1-4. Analyzing power and differential cross section excitation functions for the reaction $^{208}\text{Pb} (\bar{p}, p')^{208}\text{Pb}^*(3^-)$ at 135°, 150° and 165° in the range 17 - 18 MeV.

may cause it. The only requirement for non-zero analyzing power in inelastic scattering is that two or more partial waves in the entrance channel contribute to the scattering amplitude. Since the 3^- state is highly collective, it has a large non-resonant scattering amplitude whose interference with either the $g_{7/2}$ or $d_{3/2}$ resonance amplitude could cause structure in the excitation function. Even if there were no non-resonant amplitudes, the $g_{7/2}$ and $d_{3/2}$ resonances are nearly degenerate and could produce structure by interfering with each other. In addition, there is the possibility of "core-excited analog states" built on the $^{208}\text{Pb}$, 3^- state. The effects of these would be seen at center of mass energies 2.613 MeV higher than the ordinary analog state energy. For the case of the $g_{9/2}$ resonance this is a bombarding energy of 17.54 MeV. This probably represents a very small fragment of the wave function in the elastic channel and therefore its effect would not be observed in elastic scattering. However, the inelastic scattering might exhibit such an effect because this configuration would have a large probability for decay to the 3^- state. A proper interpretation will require additional data.
Table 10.1-1. Elastic Scattering Partial Widths Extracted from the Isobaric Analog Resonances of the Low-Lying States of $^{209}$Pb

<table>
<thead>
<tr>
<th>$\ell j$</th>
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<th>Ref. 2</th>
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<td>$g_{9/2}$</td>
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<td>$22 \pm 3$</td>
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<td></td>
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</tr>
<tr>
<td>$d_{5/2}$</td>
<td>$44.3 \pm 6.5$</td>
<td>$30 \pm 3$</td>
<td>$58 \pm 15$</td>
<td>$49.2 \pm 0.7$</td>
</tr>
<tr>
<td>$s_{1/2}$</td>
<td>$47.8 \pm 5.4$</td>
<td>$175 \pm 10$</td>
<td></td>
<td>$47.6 \pm 1.8$</td>
</tr>
<tr>
<td>$g_{7/2}$</td>
<td>$51 \pm 9$</td>
<td>$30 \pm 6$</td>
<td>$36 \pm 15$</td>
<td>$29.5 \pm 2.6$</td>
</tr>
<tr>
<td>$d_{3/2}$</td>
<td>$38 \pm 11$</td>
<td>$40 \pm 8$</td>
<td>$46 \pm 15$</td>
<td>$44.4 \pm 4.2$</td>
</tr>
</tbody>
</table>


10.2 The $^{35}\text{Si}(p,p_0)$ Reaction and the Design of a Silicon Polarimeter


It has been demonstrated that for certain applications, where good energy resolution is required, a silicon transmission detector can be a more efficient proton polarization analyzer than the more conventional carbon and helium analyzers. A silicon polarimeter is different from the usual type only in that bias is placed on the analyzer and when an elastic scattering event occurs in the analyzer, the signal from the analyzer is added to that obtained from the counter which detects the scattered proton. In an effort to design a high-resolution polarimeter for spectroscopic studies at tandem energies, we have measured thick-target differential cross section and analyzing power angular distributions at 14.34, 15.81 and 17.29 MeV.

The measurements were made using a silicon transmission counter approximately 83 microns thick (20 mg/cm$^2$) as a target. Elastically scattered protons were detected by a six-detector array of Si(Li) counters whose acceptance angles were $\pm 0.5^\circ$. The beam polarization was continuously monitored using a $^4\text{He}$ polarimeter located directly behind the target. The target was turned
40° away from normal to the beam so that the energy interval in which the reaction could occur was the same for all scattering angles. The incident beam then lost 600, 620, and 580 keV, in traversing the target, for the bombarding energies given above.

Figure 10.2-1 shows a schematic diagram of a typical double scattering experiment with a Si polarimeter. The analyzer (second scatterer) is a conventional Si ΔE detector. Second-scattered particles are stopped in the left and right E detectors.

A second scattering is indicated by coincident pulses in the ΔE detector and either of the Ε detectors. If a coincidence is detected, the two energy signals are added together to form a total energy signal. The energy resolution of the device is then somewhat inferior to that of a conventional particle identification telescope.

The analyzing power and differential cross section angular distributions are shown in Fig. 10.2-2. Over the measured energy range the nodes of the analyzing power angular distributions shift very slowly. This is crucial to the design of a silicon polarimeter since the thickness of the analyzer and therefore the energy efficiency of the polarimeter is limited by the range of energies, for a given angular acceptance, over which the analyzing power remains of one sign.

In the range 13.7 - 17.2 MeV, there are five angular ranges, listed in Table 1, in which the analyzing power always has one sign. It can be shown that the efficiency of a polarization analyzer is proportional to

\[ \int \int \frac{d\Omega}{d\Omega} \frac{d\Delta E}{d\Delta E} A^2(E,\theta) d\Omega dE \]

where ΔE is the range of energies in which the second scattering may occur in the analyzer and ΔΩ is the finite solid angle of one of the E detectors. Thus, in Table 1 the product of counts per unit charge and the square of the measured asymmetry is listed for each energy. The sum over all three energy ranges appears on the right. There are three angular ranges which clearly have higher efficiencies than the other two. Of these three, the forward and backward angular ranges are more practical since they don't require the ΔE detector to be rotated away from normal to the scattered beam. Use of the forward angle maximum is attractive since the counting rates in the left and right detectors are higher allowing faster electronics setup and troubleshooting. Also, transmission geometry for the left and right counters, in principle, allows the analyzer to be thicker for a given incident energy than would be possible with back-angle reflection geometry. The backward angle maximum very likely has less
Fig. 10.2-2. Differential cross section and analyzing power angular distributions for Si(\(\vec{p}, p_0\)) at average interaction energies of 14.0, 15.5 and 17.0 MeV.

Table 10.2-1. Unnormalized Product of Differential Cross Section and the Square of the Analyzing Power Summed over the Angular Regions where the Analyzing Power Remains One Sign

<table>
<thead>
<tr>
<th>Angular Range (Lab)</th>
<th>Sign</th>
<th>(E = 17.29)</th>
<th>(E = 15.84)</th>
<th>(E = 14.34)</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-35°</td>
<td>-</td>
<td>(2.51 \times 10^4)</td>
<td>(3.06 \times 10^4)</td>
<td>(2.36 \times 10^4)</td>
<td>(7.93 \times 10^4)</td>
</tr>
<tr>
<td>45-55°</td>
<td>+</td>
<td>(3.02 \times 10^3)</td>
<td>(5.90 \times 10^3)</td>
<td>(2.37 \times 10^4)</td>
<td>(3.26)</td>
</tr>
<tr>
<td>65-95°</td>
<td>-</td>
<td>(1.83 \times 10^4)</td>
<td>(3.32 \times 10^4)</td>
<td>(4.00 \times 10^4)</td>
<td>(8.65)</td>
</tr>
<tr>
<td>105-120°</td>
<td>+</td>
<td>(5.04 \times 10^3)</td>
<td>(6.28 \times 10^3)</td>
<td>(5.39 \times 10^3)</td>
<td>(1.77)</td>
</tr>
<tr>
<td>145-165°</td>
<td>+</td>
<td>(1.08 \times 10^4)</td>
<td>(2.00 \times 10^4)</td>
<td>(2.77 \times 10^4)</td>
<td>(5.85)</td>
</tr>
</tbody>
</table>

Severe background problems but potentially has an additional disadvantage in that the inelastic scattering cross section to the \(2^+\) first excited state is much larger relative to the elastic scattering cross section. This inelastic scattering yields satellite peaks in the summed energy spectra that lie 1.78 MeV lower in energy than the peaks corresponding to elastic scattering in the
If one can accurately predict the behavior of the Si elastic scattering angular distributions in the energy gaps not covered by these measurements, for a 17.29 MeV incident proton beam and a 628 μ thick analyzer we expect a yield of as much as $9 \times 10^{-3}$ per particle incident on the polarimeter and an average analyzing power of $-0.08$ at the forward angle maximum. The corresponding predictions for the backward angle maximum are $1.5 \times 10^{-4}$ and $0.54$.

Preliminary measurements have indicated that background counting rates in the left and right counters can be reduced to tolerable levels and reasonable summed energy spectra obtained at analyzer counting rates as high as $10^5$/sec. Other features of the design such as detector types, collimation and shielding are still under consideration.


10.3 Analyzing Power in the $^{89}\text{Y}(p,p')^{89}\text{Y}$ Reaction near the $d_5/2$ Isobaric Spin Doublet

M.P. Baker and E. Freikschat

Preliminary analyzing power excitation function measurements have been made for proton elastic scattering from $^{89}\text{Y}$ in the energy range 4.7 - 5.1 MeV. This is near the analogs of the ground ($2^-$) and first excited ($3^-$) states of $^{90}\text{Y}$. These states are thought to have very pure $(d_5/2 p_{1/2})$ configurations from $(d,p)$ studies on $^{89}\text{Y}$. It is possible though that there are admixtures of $(d_3/2 p_{1/2})$ and $(g_7/2 p_{1/2})$ configurations, respectively, in the two states.

Measurement of the analyzing power and differential cross section excitation functions near these isobaric analog resonance can yield the composition of these states since the resonance amplitudes are functions of the orbital and total angular momentum of the resonant protons. Similar measurements have been made on the analogs of higher-lying "particle-hole" states of $^{90}\text{Y}$ and have shown the configurations to be quite pure.

The excitation function data were obtained at 135° and 165° in the manner described in Section 10.1 of this report and are shown in Fig. 10.31-1. At most of the bombarding energies, the measurements were made using a $^{89}\text{Y}$ target rolled to a thickness of approximately 500 μg/cm². Thus the incident beam lost 18-19 keV in traversing the target. The $2^-$ and $3^-$ analog resonances are seen quite clearly at both angles at approximately 4.82 and 5.02 MeV, respectively. This is in agreement with previous differential cross section measurements.

In order to extract reliable resonance parameters and thus determine the configuration mixing, accurate differential cross section measurements are also
required. This is especially true in this case since compound nuclear contributions to the cross section are important at these energies.\textsuperscript{4}

In fact, Ref. 4 has a rather complete analysis of these resonances but does not touch on the question of configuration mixing. With only the analyzing power data, however, some qualitative conclusions can be drawn. For example, the dominant configuration of the two states must be the same since at a given angle the resonance shapes are so similar. Further, the relative sizes of the analyzing power on resonance at 135° and 165° are consistent with d-wave protons. Also the phases of the resonances indicate that the total angular momentum is $j^+$, i.e. the resonant protons are in a $d_{5/2}$ state.


10.4 Asymmetry of Polarized Protons Inelastically Scattered from $^{40}$Ca and $^{48}$Ca


In recent years many measurements have been made of the analyzing power of inelastically scattered protons and these have given broad support to a DWBA model for the reaction which employs not only collective form factors but also a spin-dependent interaction of the full-Thomas form. The best fits of calculation to observation often require, however, that the deformation length for the spin-dependent form factor, $\delta_{L,so} = \beta_{L,so} \delta_0$, be considerably larger than that for the spin-independent form factor, $\delta_{L} = \beta_{L} \delta_0$. Raynal has interpreted this as evidence for an isospin-dependence in the spin-dependent interaction; some isospin-dependence is to be expected since the low energy proton-proton spin orbit interaction is essentially twice the neutron-proton interaction.

To delineate this isospin dependence, we have measured the angular distributions and asymmetry when 17.5-MeV protons inelastically excite a variety of
states in $^{40}\text{Ca}$ and $^{48}\text{Ca}$. Since states of low excitation energy in $^{40}\text{Ca}$ have $T = 0$, no isospin-dependence is there expected; on the other hand, the strength of the spin-dependent interactions in $^{48}\text{Ca}$ should depend on whether the excitation involves predominantly neutron or proton particle-hole configurations.

The Lamb-shift polarized ion source was used to provide a beam of 17.5-MeV protons with an intensity of 10-15 nA and a measured polarization of 70%. The beam polarization was continuously monitored by a $^{4}\text{He}$ polarimeter located behind the primary target. A rolled target of $^{40}\text{Ca}$ (about 1 mg/cm$^2$ thick) and an evaporated target of $^{48}\text{Ca}$ (also 1 mg/cm$^2$ thick) were used for bombardment. Three pairs of 2000 micron lithium-drifted silicon detectors were used in a left-right symmetrical geometry to provide simultaneous measurement of three experimental points, 15° apart in laboratory coordinates. The angular distribution and asymmetry were measured from 20° to 110° in 5° steps and also at 120°, 135°, and 150° in the laboratory system.

At the time of this writing, only the $^{40}\text{Ca}$ spectra have been analyzed. Due to occasionally severe background, the yields to specific states in $^{40}\text{Ca}$ were extracted through hand calculation. The main contaminants in the target were $^{12}\text{C}$ (whose state at 4.43 MeV contributed a particularly bothersome peak), hydrogen, and a material with atomic mass near 27. The "mass 27" contaminant was particularly troublesome in the analysis of states of lower excitation at angles forward of 60°.

The angular distributions and asymmetries for the most strongly excited states in $^{40}\text{Ca}$ are shown in Figs. 10.4-1 and 10.4-2. Although full analyses of the $^{48}\text{Ca}$ data are not in hand, it is clear that there are often differences in the asymmetries to corresponding states of the two isotopes.

Inelastic angular distributions, asymmetries, and proton-gamma ray correlations for excitation of the 3.73 MeV 3$^-$ state by 20.3-MeV protons have previously been well fitted by Lewellen$^3$ using the model mentioned in our first paragraph. Similarly, good optical model fits to elastic cross sections and polarizations have been obtained by a group at Rutgers$^4$ for bombarding energies of 16.25 MeV and less. Unfortunately, it appears that neither a natural extrapolation of Lewellen's optical model parameters nor those of the Rutgers group lead to truly good fits to our observed inelastic asymmetry for the lowest 3$^-$ and 5$^-$ states of $^{40}\text{Ca}$. Until a better description of our $^{40}\text{Ca}$ results is available, we will be unable to make manifest the difference in asymmetries for corresponding states of $^{40}\text{Ca}$ and $^{48}\text{Ca}$.

Fig. 10.4-1. Inelastic angular distributions for excitation of various states in $^{40}$Ca by 17.5-MeV protons. The curves are drawn to aid the eye and have no theoretical significance.

Fig. 10.4-2. Inelastic asymmetries for excitation of various states in $^{40}$Ca by 17.5-MeV protons. The curves are drawn to aid the eye and have no theoretical significance.
11. REACTIONS PRODUCED BY CARBON AND OXYGEN IONS

11.1 The $^{12}\text{C}(^{12}\text{C}, ^{8}\text{Be})^{16}\text{O}$ Reaction in the Vicinity of the Quasimolecular Resonances

M.D. Cooper, P.H. Lau, and W.N. Reisdorf

Over ten years ago $^1$ three prominent sub-Coulomb resonances were observed in the scattering of $^{12}\text{C}$ at center of mass energies of 5.7, 5.0, and 6.3 MeV. The resonances appeared in nearly all outgoing channels at the same compound nucleus excitation energy. Normal compound nuclear resonances are excluded as a likely explanation since at an excitation energy of 20 MeV in $^{24}\text{Mg}$ the level separation is only a few keV. $^2$ A very special structure for these states is required for them to be prominent in such a dense level region. Also it is unlikely that these apparent resonances are statistical fluctuations since many outgoing channels resonate at the same energy. Recently the resonances have been interpreted $^3$ as intermediate structure arising from an $\alpha$-particle model for the $^{12}\text{C}$ nuclei.

The simplest first order picture of the intermediate structure is that both $^{12}\text{C}$ nuclei appear as clusters of three $\alpha$ particles. The most striking experimental observation is the unusually large reduced width for elastic carbon scattering (at least 10 times that of any other channel) and it has been proposed that an intermediate quasi-stable structure of the two carbon nuclei is responsible for these large reduced widths. If such an intermediate "quasi-molecule" exists it seems reasonable that an alpha particle might be transferred preferentially between the carbons to form $^{8}\text{Be}$ and $^{16}\text{O}$. The $\alpha$ structure of $^{8}\text{Be}$ enhances this conjecture. The observation of an anomalously large reduced width for the $^{12}\text{C}(^{12}\text{C}, ^{8}\text{Be})^{16}\text{O}$ reaction at the same resonant energies would provide strong support for such a naive model.

Last year $^4$ the feasibility of the experiment was proven when $^{8}\text{Be}$ nuclei detected in a position sensitive detector were observed in the proper kinematic coincidence with $^{16}\text{O}$ recoil nuclei in an angle defining detector. With this technique a peak to background ratio of 100:1 was obtained for center of mass angles of 63°, 74°, 83°, and 90°. In order to extend the angular range to cover angles where the kinematics are degenerate in $^{16}\text{O}$ recoil angle, a second technique was employed to reduce background in this region. Here a foil was used in front of the position detector to stop heavy ions but not the $^{8}\text{Be}$, which appears as two alpha particles of greater range. Protons passed through the detector without depositing sufficient energy to overlap the $^{8}\text{Be}$ peak and alphas from $^{20}\text{Ne} + \alpha$ were discriminated against by their recoil angle. With this second technique, excitation functions were added to the above sets of angles at 29°, 33°, 36°, 39°, 43°, 46°, 49°, 53° and 56° degrees for a total of 13 angles. The excitation functions covered 19 center of mass energies from 5.775 - 6.675 MeV in 50 keV steps. The lower boundary was set by low counting rate and prevented examination of the lowest lying resonance at 5.7 MeV. A typical excitation function is shown in Fig. 11.1-1.

Alternatively, the data can be displayed as 19 angular distributions with 13 angles each. A typical angular distribution is shown in Fig. 11.1-2. The lack
Fig. 11.1-1. $^{12}\text{C}(^{12}\text{C}, ^{8}\text{Be})^{16}\text{O}$ excitation function at $\theta_{\text{c.m.}} = 89.5^\circ$. Error bars are statistical.

Of very smooth behavior of the distribution is due to the steepness of the excitation functions. With a carbon target, the target thickness changed due to carbon deposited by the beam. Target thickness had to be corrected with a monitor detector, but the resultant averaging over a rapidly varying excitation function produced fluctuations from angle to angle. The error bars represent only statistical errors.

As mentioned, target thickness was monitored with a separate detector and the corresponding energy spread in the center of mass system never exceeded 50 keV. Absolute cross sections were obtained by normalizing the data to the elastic scattering monitor. The elastic scattering cross section was measured independently at 90° by normalizing the yields to the Coulomb cross section at

Fig. 11.1-2. $^{12}\text{C}(^{12}\text{C}, ^{8}\text{Be})^{16}\text{O}$ angular distribution at $E_{\text{c.m.}} = 5.925$. Solid line is fit to data described in text.

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Fig. 11.1-3. $^{12}\text{C}(^{12}\text{C},^{8}\text{Be})^{16}\text{O}$ partial cross sections for the $\ell$ values 0, 2 and 4. Fits are obtained by using a smoothed $\sigma_2$ cross section taken from preliminary fits.
\[ E_{\text{cm}} = 5.5 \text{ MeV}. \]

To find the contributions from each partial wave, the angular distributions were fit with a function of the form

\[ g(\theta) = \left| \sum_{\ell=0}^{\ell_{\text{max}}} a_{\ell} P_{\ell} (\theta) \right|^2 \]

where \( a_0 \) is real and \( a_{\ell} \neq 0 \) are complex. The above form is highly non-linear in the parameters of the fit and the minimum is most easily found by finding an approximate solution and then searching successively on each parameter individually. The resulting minimum can be shown to be the same as found by varying all parameters simultaneously if reasonable starting values are taken. However, problems dealing with the radius of convergence of the solution are reduced.

It was found that setting \( \ell_{\text{max}} = 4 \) was sufficient to cover the range of data taken. However, large fluctuations in one partial wave can cause effects in other partial waves if the data are not extremely good. Hence, after a trial fit was made and it was determined that there were no resonances in the \( \ell = 2 \) channel, the \( \ell = 2 \) coefficients were smoothed and new fits to \( \ell = 0 \) and \( \ell = 4 \) coefficients were obtained. A typical fit to the angular distribution is shown in Fig. 11.1–2. In Fig. 11.1–3 are shown the resulting \( \ell = 0, 2, 4 \) excitation functions for the partial cross sections, \( \sigma_{\ell} \), defined through

\[ \sigma = 4\pi \sum_{\ell \text{even}} (2\ell + 1) \sigma_{\ell} \]

where \( \sigma \) is the total integrated cross section.

Based on these curves, it can be stated with fairly high probability that the resonance near 6 MeV is \( \ell = 4 \) and strongly interfering with the background. The interference accounts for an apparent shift from 6 MeV. The resonance near 6.3 MeV appears to be \( \ell = 0 \) giving assignments of \( 4^+ \) and \( 0^+ \) to the higher two quasi-molecular states. The \( 4^+ \) assignment of the 6 MeV resonance agrees with Ref. 1.

In order to extract reasonable reduced widths for the \( ^8 \text{Be} \) channel, it is necessary to solve two problems. First, the interference effects between resonance and background must be separated. Second, the dependence of the reduced widths on the radius at which the penetrabilities are calculated must be taken into account. In Ref. 1, the radius dependence made a factor of 100 effect on the reduced width for the \( 12\text{C} \) channel.

At present our best preliminary number for the resonance strength of the \(^6\text{He} \) MeV state is based on taking the radius as 6 fm and using the peak value of \( \sigma_4 \) at \( E_{\text{cm}} = 5.925 \). The resulting value for the partial width is 1.1 keV. This implies a value for the reduced width which is intermediate in strength between that of the carbon elastic channel and the strongest other channel. The \(^8\text{Be} \)
channel is five times as strong as any other channel, excluding the elastic channel. These preliminary results seem to support an intermediate structure picture involving a cluster transfer, but the final results await a more sophisticated analysis presently in progress.


11.2 Analysis of the $^{140}$Ce($^{16}$O, $^{15}$N)$^{141}$Pr, $^{140}$Ce($^{18}$O, $^{17}$O)$^{141}$Ce, and $^{88}$Sr($^{16}$O, $^{15}$N) $^{89}$Y Experimental Excitation Functions Below and Near the Coulomb Barrier

J.S. Blair and K.G. Nair

Data on single nucleon transfer reactions induced by heavy ions near the Coulomb barrier acquired during the past year have been analyzed using the DWBA formulation of Buttle and Goldfarb. This procedure contains two leading approximations: (1) The bound state radial wave function of the transferred particle relative to the second core is fitted to a Hankel function in a region around a "match center radius", $R_2$, defined as $R_2 = \alpha[A_2^{1/3}(A_1^{1/3} + A_2^{1/3})]$, where $\alpha$ is the distance of closest approach for a head-on collision averaged between the incident and final channels. (2) Approximate account is taken of recoil through a simple modification of the effective momenta entering the distorted waves. Coulomb correction terms are also taken into account in the form factor. Above the Coulomb barrier, we replace the pure Coulomb wave functions in the entrance and exit channels by waves also distorted by a complex nuclear potential chosen to give a reasonable description of the back angle elastic scattering.

Figure 11.2-1 depicts the excitation functions for transfer to the well resolved levels in the reactions $^{140}$Ce($^{16}$O, $^{15}$N)$^{141}$Pr, $^{140}$Ce($^{18}$O, $^{17}$O)$^{141}$Ce, and $^{88}$Sr($^{16}$O, $^{15}$N)$^{89}$Y as well as the corresponding elastic excitation functions. Data on additional unresolved or incompletely resolved transitions were analyzed, but will not be discussed in this report. The continuous curves are theoretical fits. Inspection of Fig. 11.2-1 shows: (1) Below some critical energy, the pure Coulomb cross sections are identical to those calculated with nuclear optical potentials. (2) As the barrier is surmounted, there are moderate discrepancies between the observed cross sections and those calculated with optical potentials giving a good fit to elastic scattering. (3) There are moderate variations between calculations with different optical potentials even though the corresponding differences between the elastic excitation functions are much smaller.

Calculated absolute cross sections are, of course, sensitive to the
Fig. 11.2-1. Excitation functions at \( \theta_{lab} = 170^\circ \) for the reactions 

\( ^{140} \text{Ce}(^{16}_0,^{16}_0)^{140} \text{Ce}, \quad ^{140} \text{Ce}(^{16}_0,^{15}_N)^{141} \text{Pr}, \quad ^{140} \text{Ce}(^{16}_0,^{18}_0)^{140} \text{Ce}, \quad ^{140} \text{Ce}(^{18}_0,^{17}_0)^{141} \text{Ce}, \quad ^{88} \text{Sr}(^{16}_0,^{16}_0)^{88} \text{Sr}, \quad ^{88} \text{Sr}(^{16}_0,^{15}_N)^{89} \text{Y}, \) and 

\( ^{88} \text{Sr}(^{16}_0,^{15}_N)^{89} \text{Y}, \) The solid curves correspond to elastic scattering fits with appropriate sets of optical parameters, designated by numbers 1, 4, 5 and 6 and to DWBA transfer calculations with and without these optical parameters in the entrance and exit channels.

The geometry of the bound states and their spectroscopic factors. Numerical studies with a wide variety of bound state parameters indicate, though, that the absolute cross sections are essentially determined by one invariant quantity, \( P(R_1,R_2) \), the joint probability for the transferred nucleon being at radius \( R_1 \) with respect to the first core nucleus and radius \( R_2 \) with respect to the second; more specifically

\[
P(R_1,R_2) = S^{(1)} S^{(2)} |u_{k_1}(R_1)|^2 |u_{k_2}(R_2)|^2
\]
Table 11.2-1. Summary of Results

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$\xi$</th>
<th>final state</th>
<th>$E$ (MeV)</th>
<th>$P$</th>
<th>$R_1^{'P}$</th>
<th>$R_2^{'P}$</th>
<th>$\Lambda(1)/\Lambda(2)$</th>
<th>$\chi_1^\text{eff}$</th>
<th>$\chi_2^\text{eff}$</th>
<th>$S(1)$</th>
<th>$S(2)^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14_1}_{\text{Pr}}$</td>
<td>3</td>
<td>g.s.</td>
<td>56</td>
<td>2.667 x 10^{-7}</td>
<td>0.21</td>
<td>9.39</td>
<td>1.306 x 10^{5}</td>
<td>0.7184</td>
<td>0.713</td>
<td>1.727</td>
<td>0.61 ± 0.05</td>
</tr>
<tr>
<td>6</td>
<td>1.13</td>
<td>56</td>
<td>4.804 x 10^{-7}</td>
<td>0.22</td>
<td>8.71</td>
<td>8.088 x 10^{2}</td>
<td>0.7179</td>
<td>0.769</td>
<td>2.119</td>
<td>1.04 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.30</td>
<td>59</td>
<td>1.245 x 10^{-6}</td>
<td>0.22</td>
<td>8.73</td>
<td>2.672 x 10^{5}</td>
<td>0.7179</td>
<td>0.7387</td>
<td>1.727</td>
<td>0.61 ± 0.30</td>
<td></td>
</tr>
<tr>
<td>$^{89}_{\text{Y}}$</td>
<td>0</td>
<td>g.s.</td>
<td>42.5</td>
<td>7.194 x 10^{-7}</td>
<td>0.49</td>
<td>7.95</td>
<td>7.262 x 10^{4}</td>
<td>0.7184</td>
<td>0.7574</td>
<td>2.512</td>
<td>1.17 ± 0.15</td>
</tr>
<tr>
<td>5</td>
<td>0.91</td>
<td>42.5</td>
<td>1.962 x 10^{-7}</td>
<td>0.56</td>
<td>8.08</td>
<td>9.506 x 10^{2}</td>
<td>0.7183</td>
<td>0.6872</td>
<td>1.347</td>
<td>0.72 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>$^{141}_{\text{Ce}}$</td>
<td>1.3,5</td>
<td>g.s.</td>
<td>56</td>
<td>1.623 x 10^{-6}</td>
<td>0.63</td>
<td>9.21</td>
<td>1.546 x 10^{2}</td>
<td>0.5399</td>
<td>0.4598</td>
<td>1.798</td>
<td>1.11 ± 0.08</td>
</tr>
</tbody>
</table>

+ The errors assigned to $S(2)^+$ are due to counting statistics only.

where $u_{1}$ and $u_{2}$ are normalized bound state radial wave functions and $R_{1}$ is defined analogously to $R_{2}$, i.e., $R_{1} = \frac{A_{1}^{1/3}}{(A_{1}^{1/3} + A_{2}^{1/3})}$. The function $P(R_{1}, R_{2})$ is uniquely related to the product $\Lambda(1)/\Lambda(2)$ for the case of neutron transfer, where $\Lambda = N^{2}/\gamma^{3}$ as defined by Rapaport and Kerman, with $\chi$ directly related to the binding energy $B_{n}$: $\chi^{2} = (2m_{n}R_{n}^{2})$. For the case of proton transfer, $\chi$ is replaced by $\chi_{\text{eff}}$ which is a function of the "match center radius", and the relation between $\Lambda(1)/\Lambda(2)$ and $P(R_{1}, R_{2})$ is not so clear-cut. In Table 11.2-1 we have presented the joint probabilities $P(R_{1}, R_{2}), \Lambda(1)/\Lambda(2)$ and other relevant quantities for the well resolved states.

The bound state parameters used in these calculations were $r_{01} = r_{0c} = 1.20 F$, $a_{1} = 0.65 F$ for the nucleon bound to the light donor nucleus and $r_{02} = r_{0c} = 1.24 F$, $a_{2} = 0.65 F$ for the nucleon bound to the heavy acceptor nucleus. The value of the spin-orbit potential $V_{SO}$ was assumed to be 7.0 MeV throughout. Assuming $S(1) = 2.14$ for the $1/2^{+}$ state in $^{180}$ and $S(2) = 1.62$ for the $5/2^{+}$ state in $^{180}$, values of the spectroscopic factors $S(2)$ for the heavy acceptor nuclear states are obtained and are listed in the last column of Table 11.2-1. These values are, in general, close to the values obtained by light ion induced reactions.

To summarize, sub-Coulomb transfer reactions will provide very accurate determinations of the joint probability function $P(R_{1}, R_{2})$, once accurate determination of cross sections with recoil effects fully taken into account are possible. Further, systematic studies will narrow the ambiguity in spectroscopic information which pertains specifically to the heavy core.

2. P.J.A. Buttle and L.J.B. Goldfarb, Nucl. Phys. 78, 409 (1966); A115, 461
Evidence for Two-Neutron Exchange in the Elastic and Inelastic Scattering of $^{18}_0$ by $^{16}_0$

P.H. Lau, W.N. Reisdorf, and R. Vandenbosch

There has been considerable interest in recent years in the elastic scattering of heavy ions by target nuclei of comparable mass. The large cross-sections and prominent gross structure in the elastic scattering of $^{16}_0$ by $^{16}_0$ has been interpreted in terms of an $l$-dependence of the imaginary potential. The absence of similar structure in the $^{18}_0 + ^{18}_0$ system supports this interpretation. The anomalously large back angle scattering in a number of non-identical particle systems has been variously attributed to $l$-dependence and to elastic transfer. For bombarding energies above the Coulomb barrier elastic transfer is expected to be most prominent at backward angles. A reaction defined as elastic transfer occurring at a forward angle $\theta$ will correspond to the reaction defined as elastic scattering at the angle $\pi - \theta$.

We have recently obtained evidence for the contribution of two-neutron transfer to the apparent elastic and inelastic cross sections in the $^{16}_0 + ^{18}_0$ system. These results were obtained in the course of a comprehensive study of the elastic, inelastic and transfer reactions for the $^{16}_0 + ^{18}_0$ and $^{18}_0 + ^{18}_0$ systems described previously.

Angular distributions for the $^{15}_0(^{18}_0, ^{18}_0)^{16}_0$ reaction at two energies are illustrated in Fig. 11.3-1. The points at backward angles were actually obtained by observing the $^{16}_0$ recoil in the forward direction. This technique allows a fairly large angular range to be investigated. Thus the anomalous features reported here were not noticed in the study of Siemssen et al., where cross sections were not obtained at angles greater than $100^\circ$, nor in the low-energy measurements of Cobbi et al. The present data exhibit a somewhat damped but regular oscillatory behavior for angles forward of approximately $100^\circ$. As one goes to more backward angles the diffraction structure becomes less regular and at still larger angles the cross section starts to rise considerably. The anomalous behavior at backward angles can be made more apparent by comparison with optical model calculations. The dotted curve is based on a fit to the experimental data in the forward hemisphere. The parameters obtained are fairly similar to those found by Siemssen et al. This fit predicts a continual decrease in the cross section with increasing angle, contrary to the observations. We next attempted to reproduce the back-angle data by making the imaginary potential explicitly $l$-dependent. If the critical angular momentum was chosen sufficiently small to reproduce the back-angle peaking, a poor account of the cross section at intermediate and forward angles resulted as illustrated by the full curve in Fig. 11.3-1. It was also not possible to obtain the correct phasing.
Fig. 11.3-1. Elastic scattering angular distributions. The dashed curve is an optical model fit to the forward angle data with $r_y = 1.35 (A_1^{1/3}+A_2^{1/3})$, $r_w = 1.32 (A_1^{1/3}+A_2^{1/3})$, $v = 13.7 + 0.2 E_{c.m.}$, $W = 0.2 + 0.22 E_{c.m.}$, $\Delta v = 0.56$, and $\Delta W = 0.5$. The heavy full curve is for the same potential but with an $\ell$-dependence of the imaginary potential given by $l_c = 16$ at $E = 19.7$ and 19.3 at $E = 24.4$ and $\Delta l = 0.5$ at both energies. The dot-dashed curves at backward angles are the $^{16}_O(^{18}_O,^{16}_O)^{20}_O$ (g.s.) cross-sections obtained at the same laboratory bombarding energies.

Fig. 11.3-2. Inelastic scattering to the 1.98 MeV 2+ level of $^{18}_O$. The dashed curves are coupled-channels calculations with $\beta_2 R = 1.08 F$ and essentially the same optical potential used to calculate the dashed fits in Fig. 11.3-1. The dot-dashed curves at backward angles are the $^{18}_O(^{18}_O,^{18}_O)^{20}_O$ (1.67 MeV 2+ level) angular distributions obtained at the same laboratory bombarding energies.

at both forward and backward angles. Although the present results show that the back-angle peaking in the $^{18}_O(^{18}_O,^{18}_O)^{16}_O$ reaction is not solely due to an $\ell$-dependence of the imaginary potential, we note that there remains some evidence for a modest $\ell$-dependence in that the fits to the intermediate-angle portions of the angular distributions have been improved by allowing a smaller radius for the imaginary potential than for the real potential.

We now turn to the results for inelastic scattering to the 1.98 MeV 2+ level of $^{18}_O$ illustrated in Fig. 11.3-2. The data have been compared with a coupled channels calculation assuming a deformation length $\beta_2 R$ of 1.08 F. This
value is in good agreement with the values (0.9-1.1) found in proton and alpha particle scattering. Again the inelastic cross section at back angles far exceeds the predicted values.

We believe the anomalous behavior in the back-angle scattering can be attributed to a contribution from two-neutron elastic transfer. Support for this suggestion is obtained by comparison with the two-neutron transfer cross sections we have observed in the $^{180}(^{180},^{180})^{200}$ reaction. These cross sections are comparable in magnitude to the back-angle elastic and inelastic scattering. The two-neutron transfer cross sections in the $^{180} + ^{180}$ system at the same laboratory energy are shown as the dot-dashed curves at back angles in Figs. 11.3-1 and -2. This comparison provides only a rough estimate of the expected magnitude and angular distribution for two-neutron transfer in the $^{160} + ^{120}$ system in view of the fact that both the center of mass energies and the final nuclei are different. Moreover one system involves identical particles and the other does not. Two-neutron transfer via the $(t,p)$ reaction populates the ground and first excited states in $^{180}$ somewhat stronger than does the same reaction to the corresponding states in $^{200}$. These results are consistent with the comparisons in Figs. 11.3-1 and -2. We therefore conclude that a two-neutron transfer contribution of approximately the correct strength to account for the back-angle anomaly is expected on the basis of other evidence.

11.4 Elastic Scattering of $^{12}\text{C}$ by $^{20}\text{Ne}$

R. Vandenbosch and M.P. Webb

An investigation of the elastic scattering of $^{12}\text{C}$ from $^{20}\text{Ne}$ was initiated this year. The impetus for this experiment is provided by the need to understand the observation of the striking oscillatory structure in the elastic scattering excitation function of $^{16}\text{O} + ^{16}\text{O}$ in the energy region 20-35 MeV c.m. We attempted to confirm the suggestion\(^1\) that the aforementioned structure is the result of the absence of direct reaction exit channels which may carry away the angular momentum brought in through the entrance channel (associated with those partial $l$-waves undergoing a grazing collision). Unlike the case for $^{16}\text{O}$ (a doubly closed shell nucleus), many of the direct reaction exit channels for $^{12}\text{C} + ^{20}\text{Ne}$ are not inhibited by angular momentum considerations, implying an excitation function for elastic scattering considerably damped compared to $^{16}\text{O} + ^{16}\text{O}$). Alternative explanations\(^2,\(^3\) for the large elastic cross section for $^{16}\text{O} + ^{16}\text{O}$ invoke the compound nuclear level densities or the decay widths of the compound nucleus. Since the $^{12}\text{C} + ^{20}\text{Ne}$ reaction forms the same compound nucleus as $^{16}\text{O} + ^{16}\text{O}$, one would expect large elastic cross sections for $^{12}\text{C} + ^{20}\text{Ne}$ elastic scattering if the latter explanations are valid.

The initial phases of this inquiry were carried out utilizing a gas target ($^{20}\text{Ne}$ pressure ~50 torr) with 0.1 mil havar windows and a transmission mounted solid state detector. The energy losses suffered by the incident and recoil $^{12}\text{C}$ in the havar were calculated to be 20-50% of the bombarding energy, depending on the angle of detection. At 40 MeV bombarding energy the elastic scattering peak was clearly identifiable at the lab angles 25, 31.7, 38.3, 45 and 52°. At 59.3° (90° c.m.) the elastic peak merged into the low energy background. An attempt to reduce the background by an anticoincidence arrangement was only partially successful. Further attempts with a thinner transmission counter or utilization of a coincidence with the recoil particle will be made.


11.5 Elastic and Inelastic Scattering of $^{16}\text{O}$ from $^{26}\text{Mg}$, $^{27}\text{Al}$, and $^{28}\text{Si}$

J.G. Cramer, R.M. DeVries, K.-L. Liu, K.G. Nair, and M.S. Zisman

We have begun a study of elastic and inelastic scattering of heavy ions from sd-shell targets. The purpose of this study is to obtain systematic information regarding the appropriate optical potentials to use in DWBA calculations for this mass region. In this initial experiment we employed 100 µg/cm² targets of $^{26}\text{Mg}$, $^{27}\text{Al}$, and $^{28}\text{Si}$ (on 10 µg/cm² carbon backings).

The outgoing $^{16}\text{O}$ ions were detected in an array of 9 Si surface barrier
Fig. 11.5-1. Spectrum obtained from single detector measurements of $^{16}$O scattering on $^{28}$Si.

detectors fabricated in this laboratory. The solid angles of the detectors ranged from 0.4 to 4 msr in order to follow the rapid decrease in the elastic scattering cross sections at backward angles. All of the targets were studied at a fixed center of mass energy, $E_{c.m.} = 42$ MeV. A typical spectrum for the $^{28}$Si target is shown in Fig. 11.5-1. The resolution was about 500 keV FWHM and was due both to the target thickness and the angular acceptance of the detectors.

Figure 11.5-2 shows elastic scattering angular distributions for the three targets over the angular range $15^\circ < \theta_{c.m.} < 55^\circ$. Absolute cross sections were obtained by normalizing to optical model predictions at the two most forward angles. The relative counter normalizations were obtained by measuring elastic scattering from $^{197}$Au. For 66 MeV $^{16}$O ions, the cross sections from the gold target follow the Rutherford prediction at all angles.

Since it is well known\(^1\) that heavy ion elastic scattering on light targets sometimes shows strong resonant behavior, an excitation function was obtained for the $^{28}$Si target in 13 steps between $E_{lab} = 66$ to 70 MeV at center of mass angles of 31.3\(^\circ\), 39.0\(^\circ\), 46.5\(^\circ\), and 54.2\(^\circ\). The results, shown in Fig. 11.5-3, indicate that both the ground state and 1.78 MeV $2^+$ cross sections vary smoothly with energy. Similar results were obtained in a lower energy excitation function\(^2\) where the energy dependence of the elastic scattering of $^{16}$O on $^{26}$Mg was found to be quite regular for scattering angles less than 60\(^\circ\) over an energy range from 30 to 55 MeV.

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\(^1\) The excitation function for the elastic scattering of $^{16}$O on $^{28}$Si was measured in steps of 1 MeV.

\(^2\) The excitation function for the elastic scattering of $^{16}$O on $^{26}$Mg was measured in steps of 2 MeV.
The elastic scattering data are being analyzed with a heavy ion version of the optical model code GENOA. Figure 11.5-4 shows the experimental angular distribution from the $^{28}$Si target, along with the predictions of three different optical potentials. The "Brookhaven" potential is a weakly absorbing potential which was used by Auerbach et al. to fit anomalous forward-peaked ($^{18}$O, $^{16}$O) angular distributions from the lighter Ni isotopes, and the "Argonne" potential was used by Körner et al. to fit ($^{16}$O, $^{15}$N) data in the fp-shell. The "Seattle" potential ($V = 100$ MeV, $W = 61.5$ MeV, $r = 1.02$ fm, $a = 0.69$ fm) represents our best four-parameter fit to all of the $^{16}$O elastic scattering data obtained here. It is

Fig. 11.5-3. Excitation functions for elastic and inelastic scattering.

Fig. 11.5-4. Elastic scattering angular distributions and three theoretical optical model predictions as discussed in the text.
strongly absorbing, as is the Argonne potential, and differs from the latter most noticeably in geometry, having a smaller radius and larger diffuseness. As shown in Fig. 11.5-2, the Seattle potential gives good fits to the elastic scattering from all three targets studied. From Fig. 11.5-4 it is obvious that the present data require a strongly absorbing potential with a small radius in order to properly predict the envelope and the lack of structure at back angles \( \sigma/\sigma_R \approx 10^{-2} \) to \( 10^{-3} \).

We have also measured elastic scattering angular distributions of \(^{16}\text{O} + ^{28}\text{Si}\) at \( E_{\text{lab}} = 72 \) and 81 MeV. The results, along with optical model fits, are shown in Fig. 11.5-5. Again the fits using the Seattle potential are satisfactory at all energies. Thus, we find that a single four-parameter optical potential is capable of describing all of our \(^{16}\text{O}\) elastic scattering data. The inelastic scattering data have not yet been analyzed but are expected to help determine the optical model parameters.\(^6\) However, a coupled-channels approach may be necessary.\(^7\)

We plan to continue this work using high energy \(^{12}\text{C}\) and \(^{14}\text{N}\) beams to study the projectile dependence of the optical potential. This will hopefully eliminate the present need to use the same optical parameters for both entrance and exit channels in a DWBA calculation. This mass region is of particular interest at Tandem energies since, with the 81 MeV \(^{16}\text{O}\) beam available here, we can look carefully at the recoil effects which are expected\(^8\) to be very important for high energy heavy ion beams incident on light targets.

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3. Optical model search code GENOA, written by F.G. Perey.
11.6 Travels with LOLA

R.M. DeVries

The DWBA code LOLA which exactly treats finite range and recoil effects has been put into operation on the university of Washington CDC 6400 computer. The present version includes up to 64 partial waves and a 150 partial wave version will be installed soon. The program requires 124500 octal words and 3 scratch disk units. Calculations are usually divided into two parts: a) the two-dimensional form factors ("kernels") are computed and stored on permanent files, b) the final double integration and cross section calculation is performed. A typical time for a heavy ion reaction involving 80 integration steps (Δr = 0.2 usually), 40 partial waves and λ-transfers of 2 and 3 is about 45 minutes. There is an excellent chance that these computational times will be considerably reduced soon.

In heavy ion transfer reactions it appears that recoil effects are quite important, affecting both shape and magnitude of the DWBA predictions and allowing certain λ-transfers forbidden in non-recoil DWBA theories.¹ Thus the code allows quantitative predictions to be made which are not possible in approximate DWBA treatments. An example is shown in Fig. 11.6-1 for the \(^{12}\text{C}(^{16}\text{O},^{12}\text{C})^{16}\text{O}\) reaction for the data of Ref. 2. The derived spectroscopic factors are: \((^{16}\text{O} = ^{12}\text{C}_{\text{g.s.}} + \alpha) = 0.55\).

Fig. 11.6-1. Calculations for the \(^{12}\text{C}(^{16}\text{O},^{12}\text{C})^{16}\text{O}\) reaction corresponding to backward angle elastic scattering.
and \( \langle 16^0 = 12^0 \rangle = 0.71 \). This result may be very useful for analyzing these "\( \alpha \)-transfer" reactions. 3

2. H. Gutbrod et al., to be published.
3. R.M. DeVries, to be published.

11.7 Experimental Investigations of the \( 122,124_{\text{Sn}} ^{16,15}_{\text{N}} \)\( 123,125_{\text{Sb}} \) Reactions near the Coulomb Barrier

J.S. Blair, K.G. Nair, D. Potter and W. Reisdorf

Measurements of the excitation functions of proton stripping reactions induced by \( 16^0 \) bombarding \( 122_{\text{Sn}} \) and \( 124_{\text{Sn}} \) were undertaken as a continuation of the series of studies\(^1\) conducted in the past on similar reactions in \( 68_{\text{Sr}} \) and \( 140_{\text{Ce}} \). Conjeaud et al.\(^2\) have made exhaustive studies of the \( (3^0_{\text{He}},d) \) reactions on even tin isotopes at an incident energy of 18 MeV. Thus a comparison of our results with theirs could be made to highlight the similarities and differences between heavy ion induced transfer reactions below the Coulomb barrier and light ion induced reactions above the barrier. In addition, calculations of energy levels made on nuclei in this region by Kisslinger and Sorensen\(^3\) serve as standard comparison between theory and experiment.

Thin \( 122_{\text{Sn}} \) and \( 124_{\text{Sn}} \) targets of thicknesses of approximately 20 \( \mu g/cm^2 \) on carbon backings of about 15 \( \mu g/cm^2 \) thickness were bombarded with \( 16^0 \) beams of energies varying from 42 MeV to 57 MeV. The excitation functions for elastic, inelastic and \( (16^0, 15N) \) reactions populating the low-lying levels of \( 123_{\text{Sb}} \) and \( 125_{\text{Sb}} \) were measured in a quadruple detector array of four detectors placed symmetrically at 170° with respect to the beam direction.

In Fig. 11.7-1, the ratios \( \sigma/\sigma_R \) as well as the center of mass differential cross sections for the appropriate

![Fig. 11.7-1. Excitation functions for elastic scattering and proton stripping reactions to various final states when \( 122_{\text{Sn}} \) and \( 124_{\text{Sn}} \) targets are bombarded with \( 16^0 \) ions.](image-url)
\(^{16} \text{O}, ^{15} \text{N}\) reactions to the various states in the residual nuclei are given as a
function of incident energy. The continuous lines in the figure are drawn only
to guide the eye and do not indicate theoretical fits. The inelastic scattering
data taken for the first excited \(^{2+}\) states in \(^{122}\text{Sn}\) and \(^{124}\text{Sn}\) are not shown in
the figure. Theoretical calculations for these reactions based on the procedure
reported elsewhere\(^4\) are in progress.

1. Nuclear Physics Laboratory Annual Report, University of Washington (1972),
   pp. 119, 125.
4. Section 11.2 of this Report.
12. GAMMA RAYS

12.1 The $^{11}\text{B}(p,\gamma_0 \text{ and } \gamma_1)^{12}\text{C}$ Reactions above the Giant Dipole Resonance

M. Hasinoff, B. Lim, and K.A. Snover

Various calculations predict significant dipole strength well above the main GDR peaks in $^{12}\text{C}$, which lie between 22 and 26 MeV excitation energy. Gillet and Vin Mau predict a 1s$\frac{1}{2}$ to 1p$\frac{1}{2}$ component to the GDR at an excitation energy of $E_X = 34$ MeV, while the more recent calculation of Rowe and Wong predicts significant additional dipole strength in the $E_X = 40$ to 50 MeV region. In Fig. 12.1-1 is shown the 90° yield of the $^{11}\text{B}(p,\gamma_0)$ and $^{11}\text{B}(p,\gamma_1)^{12}\text{C}$ reactions from $E_p = 17.5$ to 23.4 MeV, corresponding to $E_X = 32$ to 37.5 MeV, obtained with the large NaI detector. No significant structure is seen in these data, which are consistent with a smooth decrease in the cross section from lower energies.

Fig. 12.1-1. The yields of the $^{11}\text{B}(p,\gamma_0)$ and $^{11}\text{B}(p,\gamma_1)^{12}\text{C}$ reactions. Yields were obtained by line shape analysis of the y-ray spectra, and have not been corrected for the smooth but small decrease in detector efficiency over this energy range.

3. Section 4.2 of this Report.

12.2 The 15.11 MeV($1^+, T = 1 \rightarrow 4.43 \text{ MeV}(2^+, T = 0$) Gamma-Branch in $^{12}\text{C}$

M.D. Hasinoff, B. Lim, and K.A. Snover

In a recent accurate measurement of the y-decay branches of the 15.11 MeV $1^+, T = 1$ level of $^{12}\text{C}$, results differed by factors of 1.5 to 2.0 from a previous measurement of the same quantities. The results of Ref. 1 were, however, in agreement within errors with previous, less accurate measurements (see Table 12.2-1) of the 15.11 MeV $1^+, T = 1 \rightarrow 4.43 \text{ MeV}(2^+, T = 0$) y-branch, while the results of Ref. 2 were not. It seemed worthwhile to make an independent determination of this y-branch in order to better ascertain the relative standing of the measure-
Table 12.2-1. Gamma Branches of the
15.11 MeV 1+ , T = 1 Level of 12C

<table>
<thead>
<tr>
<th>Final State</th>
<th>γ-Branch (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 MeV 0+</td>
<td>92 ± 2(^a)</td>
</tr>
<tr>
<td>4.43 MeV 2+</td>
<td>94 ± 1(^b)</td>
</tr>
<tr>
<td></td>
<td>2.3 ± 0.5(^a)</td>
</tr>
<tr>
<td></td>
<td>1.5 ± 0.3(^b)</td>
</tr>
<tr>
<td></td>
<td>3.5 ± 1(^c)</td>
</tr>
<tr>
<td></td>
<td>3.1 ± 0.6(^d)</td>
</tr>
<tr>
<td></td>
<td>4 ± 1(^e)</td>
</tr>
<tr>
<td></td>
<td>2.15 ± 0.25(^f)</td>
</tr>
</tbody>
</table>

\(^a\) Ref. 1
\(^b\) Ref. 2
\(^c\) Previous measurements as quoted in Ref. 1.
\(^d\) Present work.

In the present work, the branching ratio (15.11 → 4.43)/(15.11 → 0.0) was deduced from the singles spectrum of γ-rays observed from the bombardment of 12C with protons of energy \(E_p = 19.3\) and 20.5 MeV. Figure 12.2-1 shows one such spectrum obtained using the large NaI detector. The strong 15.11 and 12.71 MeV γ-rays are from ground-state decays of the 15.11 MeV 1+ , T = 1 and 12.71 MeV 1+ , T = 0 levels in 12C excited by inelastic scattering. Also apparent is a γ-ray of energy 10.63 ± 0.06 MeV which is identified as the 10.67 MeV γ-ray from the 15.11 → 4.43 MeV decay. Capture γ-rays apparent in the spectrum at higher energies have a negligible intensity relative to the lines of interest.

The γ-ray response function for the detector in its present geometry and with the present electronic configuration was determined from these data using a smooth extrapolation of the lineshape tails (this branching ratio is essentially independent of the method of tail extrapolation). The smooth curve in Fig. 12.2-1 represents a least-squares fit using such lineshapes.

Now the angular distributions of the γ-rays from the 15.11 → 0.0 and 15.11 → 4.43 transitions are restricted by the J = 1 spin of the intermediate state to be of the form \(A_0 + A_2P_2(\cos \theta)\); hence measurements at the \(\theta = 55^\circ\) zero of \(P_2\) directly yield the branching ratio after correcting the yields for the relative efficiency of the γ-detection. After correcting the measured yields for
the difference in absorption between the NaI crystal and the target for the two different γ-rays (an effect of 3%), the branching ratio was computed in 2 different ways: 1) directly from a least-squares lineshape fit to the total (accepted plus rejected) spectrum, and 2) from a lineshape fit to the accepted spectrum alone, along with an estimation of the electronic accepted/total ratio taken from Ref. 3. The net result is a branching ratio of 2.32 ± 0.25% where the uncertainty results from folding ±0.2% from uncertainty in the 15.11 + 12.71 MeV tail extrapolations in the region of 10.7 MeV, with ±0.1% from a systematic discrepancy in the 2 methods of computation (other contributions to the uncertainty, such as statistics, are negligible).

This result, combined with the measured value of 92 ± 2% for the 15.11 + 0.0 branch yields a value of 2.15 ± 0.25% for the 15.11 + 4.43 branch (see Table 12.2-1). This value is in good agreement with the measurement of Ref. 1, and is 40% higher than the value quoted in Ref. 2.

**Department of Physics, University of British Columbia.**


**12.3 Inelastic Proton Scattering to the 12.7 and 15.11 MeV Levels in $^{12}$C**

K. Ebisawa, M. Hasinoff, S.T. Lim, D.F. Measday, T.J. Mulligan, and J.E. Spuller

Our study of inelastic proton scattering to the T = 0 and T = 1 levels of $^{12}$C at 12.7 and 15.1 MeV through observation of the subsequent gamma radiation has continued. In particular, more accurate yield curves for both the 12.7 and 15.1 MeV gamma-rays have been measured at $\theta_{\gamma} = 55^\circ$ for $E_p > 18.6$ MeV using a $10''\times 10''$ NaI spectrometer. The increased size and better resolution of the larger NaI enabled us to obtain considerably better data for $\gamma_{12.7}$.

Figure 12.3-1 shows the yield curve for both $\gamma_{12.7}$ and $\gamma_{15.1}$ obtained at $55^\circ$ to the beam direction. Since the angular distribution for a $1^+ \rightarrow 0^+$ transition must be symmetric about $90^\circ$ and can have terms only up to $P_2$ the $55^\circ$ yield curves represent the total cross section. Also, interference contributions from overlapping resonances are mostly eliminated from the $55^\circ$ yield curve since only resonances with $I_f = 0^+$ are present.

**Fig. 12.3-1.** Gamma ray yield curves for the reactions $^{12}$C(p, p'γ) measured at $\theta_{\gamma} = 55$ degrees to the beam direction.
identical \( J^\pi \) can produce interference in the total cross section.

The 15.1 MeV yield curve at 55° is quite similar to the previous 90° yield curve\(^2\) except that the state at \( E_p = 19.75 \) MeV is more prominent. The 12.7 MeV yield curve shows three broad states at \( E_p = 18.7, 19.5 \) and 20.3 MeV in agreement with the \( ^{12}\text{C}(p,p')^{12}\text{C} \) results of Levine and Parker.\(^3\) There seems to be little apparent correlation between the yield curves for the 12.71 and the 15.11 MeV \( \gamma \)-rays. Since the formation of \( T = 3/2 \) states in the \( ^{12}\text{C} + \text{p} \) system is isospin forbidden and the decay of \( T = 1/2 \) states to both \( T = 0 \) and \( T = 1 \) final states in \( ^{12}\text{C} \) is isospin allowed, it is likely that all the broad states we observe have \( T = 1/2 \), but one would then expect the yield curves of the 12.71 and 15.11 MeV \( \gamma \)-rays to be similar.

The 15.1 MeV peaks we observe are listed in Table 12.3-1 together with the peak at 15.22 MeV observed in the previous 12.71 MeV yield curve.\(^2\) The inelastic proton widths are obtained by fitting Breit-Wigner resonances to the cross-sections using the spin assignments given neglecting any non-resonant yield. The proton widths could be in error by a factor of two or more, but nevertheless serve to indicate that inelastic proton scattering is the dominant feature of these resonances.

<table>
<thead>
<tr>
<th>( E_p ) (MeV)</th>
<th>( E_x ) (MeV)</th>
<th>( J^\pi )</th>
<th>( \Gamma ) (keV)</th>
<th>( \Gamma ) (keV)</th>
<th>( \Gamma ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.27 ± 0.07</td>
<td>16.02</td>
<td>7/2(^+)(^a)</td>
<td>( \sim 130 )</td>
<td>( \sim 7.5(^a) )</td>
<td>30</td>
</tr>
<tr>
<td>19.35 ± 0.20</td>
<td>19.77</td>
<td>5/2(^+)(^c)</td>
<td>( \sim 800 )</td>
<td>( \sim 80(^b) )</td>
<td>?</td>
</tr>
<tr>
<td>20.55 ± 0.30</td>
<td>20.87</td>
<td>5/2(^+)(^c)</td>
<td>( \sim 1100 )</td>
<td>( \sim 110(^b) )</td>
<td>?</td>
</tr>
<tr>
<td>22.2 ± 0.50</td>
<td>22.7</td>
<td>5/2(^-)(^c)</td>
<td>( \sim 2000 )</td>
<td>( \sim 200(^b) )</td>
<td>( \sim 450 )</td>
</tr>
</tbody>
</table>

a. Levine and Parker.
b. We estimate \( \Gamma_{po}/\Gamma = 0.1 \), see Lowe and Watson (1966).
c. Estimated; see Scott et al. (1967).

* Department of Physics, University of British Columbia.
1. Section 4.2 of this Report.
12.4 Capture Measurements of Protons on $^{12}$C: The Energy Region $16 \text{ MeV} \leq E_p \leq 19 \text{ MeV}$

K. Ebisawa, M.D. Hasinoff, D.L. Johnson, B. Lin, and K.A. Snover

Very little detailed experimental information exists on $(p, \gamma)$ capture reactions into the GDR of $A = 4n + 1$ light nuclei, where $n$ is an integer. This is partly due to the low $Q$-value for this sort of reaction, and also due to the need for greater $\gamma$-ray resolution to resolve the final states. Here at the University of Washington with the large U.B.C. NaI detector and the double FN tandem accelerator we have the facilities for making such measurements well up into the GDR region.

The case of $^{12}$C$(p, \gamma_0)^{13}$N is a good example of this type of capture reaction. In addition, it would be interesting to see if any of the $T = 3/2$ compound resonances in $^{13}$N previously observed in the $^{12}$C$(p, p'\gamma)^{12}$C reaction are observable in the $(p, \gamma_0)$ reaction -- this would yield information on the $\gamma$-decay widths and also on the spins and parities of these resonances.

In the present work, the excitation function for the $^{12}$C$(p, \gamma_0)^{13}$N reaction was measured between the pygmy giant resonance and the giant dipole resonance in $^{13}$N. Since the incident proton energies ($16 \text{ MeV} \leq E_p \leq 19 \text{ MeV}$) exceed the threshold for producing the 12.71 MeV and 15.11 MeV excited states of $^{12}$C, good resolution was needed to separate the capture gamma-rays from the huge amount of gamma radiation produced by inelastic scattering.

The U.B.C. detector (25 cm x 25 cm NaI) was used together with the usual pulse handling circuits and had a resolution of 4.0% (FWHM) for the 15.11 MeV gamma-rays of $^{12}$C. The shape of this line was used for a least squares fit of the present data.

A typical spectrum and fit is shown in Fig. 12.4-1. The natural carbon target was 1.4 mg/cm$^2$ thick. The excitation functions for $(p, \gamma_0)$ were all taken at 90$^\circ$ to the beam. At the same time, excitation functions were also taken for the 15.11 MeV and 12.71 MeV gamma-rays associated with the decay in $^{12}$C of the $1^+_1, T = 1$ and the $1^+_2, T = 0$ states respectively. These excitation functions

Fig. 12.4-1. Pulse height spectrum of gamma-rays produced by 18.2 MeV protons incident on $^{12}$C. The solid line is the least squares fit to the data.
are shown in Fig. 12.4-2.

The yield of the 15.11 MeV gamma-ray was found to be in agreement with that of Snover et al. The large cross section for the 15.11 MeV gamma ray at the $E_p = 17.3$ MeV resonance and above $E_p = 19$ MeV caused difficulty in the analysis of the ground state capture gamma-ray (as shown by the error bars). No correlation is evident between cross sections for the different reactions. The ground state capture cross section is flat and of magnitude 1.5 ub/sr below $E_p = 18$ MeV. Above this energy it increases sharply toward the giant resonance.

In order to improve the results and extend the measurements to higher energies, we are working on increasing the resolution and improving the pile-up rejection.

\[ \frac{\text{yield}}{\text{per GeV}} \]

\[ \begin{array}{c}
\text{12C}(p,p'\gamma)12C \\
\text{15.11 MeV GAMMA-RAY}\end{array} \]

\[ \begin{array}{c}
\text{12C}(p,p'\gamma)12C \\
\text{2.71 MeV GAMMA-RAY}\end{array} \]

\[ \begin{array}{c}
\text{12C}(p,p'\gamma)12C \\
\text{90° CROSS SECTION (ub/MeV)}\end{array} \]

\[ \begin{array}{c}
\text{PROTON ENERGY (MeV)}\end{array} \]

---

\[ \frac{\text{12C}(p,p'\gamma)12C}{\text{15.11 MeV GAMMA-RAY}} \]

\[ \frac{\text{12C}(p,p'\gamma)12C}{\text{2.71 MeV GAMMA-RAY}} \]

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12.5 Low Energy Proton Capture by $^{12}$C and the Application of a Coupled-Channels Approach to Its Description

K. Ebisawa, D.L. Johnson, K.-L. Liu, and H. Wieman

The main point of this project is to see if the low energy region of the $^{12}$C($p,Y_0)13N$ excitation function can be explained through a model involving the strong excitation of the $2^+$ state of the target nucleus. This possibility is suggested by the work of Mikoshiba, Terasawa, and Tanifuji who showed that the low energy data for the scattering of nucleons by $^{12}$C can be remarkably reproduced by a coupled-channels calculation which includes only the ground and the $2^+$ first excited core state of $^{12}$C.

To illustrate how the excitation of the $2^+$ state could bear on the capture of low energy protons by $^{12}$C, we show in a schematic diagram the direct and some of the additional amplitudes for El capture to the ground state of $^{13}$N which
Fig. 12.5-1. A schematic diagram of the process for El nucleon capture by $^{12}$C through the $3/2^+$ incident channel where channel coupling effects are included. After collision the compound system can de-excite by El single particle transitions with the core states as spectators.

occur in this model. The diagram in Fig. 12.5-1 shows a $d_{5/2}$ incident proton exciting the $0^+$ target to various combinations of core states coupled to single protons followed by El single particle transitions to the ground state. The ground state of $^{13}$N must contain a substantial amount of the configuration involving the $2^+$ state of the $^{12}$C core, otherwise the new amplitudes would be too small to matter. The wave functions of Cohen and Kurath indicate that the $2^+$ configuration in the ground state is indeed large.

Experimental Observations

Prior to our initial measurements reported last year data on $^{12}$C(p,$y_0$)$^{13}$N reaction existed only in the lowest region covered by the coupled-channels calculation ($E_p \leq 8$ MeV). Our measurements of the excitation function at $90^\circ$ have been extended to see if interesting features could be compared to the model and now span the range $E_p = 2.69$ to $8.96$ MeV. The spectra were measured with a $7.6$ cm diameter $\times 15.2$ cm long NaI crystal inside an anti-coincidence annulus crystal also made of NaI.

Since the Q-value for the $^{12}$C(p,$y_0$)$^{13}$N reaction is only 1.94 MeV, the capture gamma-rays lie in the same region of the spectrum as does background due to neutron interactions and contaminant gamma-rays. To eliminate the neutron-produced background the time-of-flight technique with a pulsed beam was used.

Figure 12.5-2 shows a scintillation spectrum following bombardment with 6.5 MeV protons. Here the dashed line represents all pulses in the detector not in the gamma-flash time window; most of this background was due to thermal neutrons. The solid line is the spectrum corresponding to the gamma-flash and illustrates where some additional problems arise. The first problem is that associated with the
peak at 8.38 MeV. This peak is due to the pile-up of two 4.44 MeV gamma-rays from $^{12}\text{C}(p,p'\gamma)$ which result from the same beam burst. This pile-up is not rejected by the pile-up rejection circuit and consequently one must drastically reduce the beam current to minimize its effect. The data near $E_p \approx 7.5$ MeV had to be rejected because the beam intensity there had not been reduced enough; in this energy region the ground state gamma-ray and the pile-up peak have nearly the same energy and cannot be resolved. The pile-up was also troublesome at lower proton energies where the $p,p'$ reaction was strong because the tail of the response function extended under the $\gamma_0$ peak.

The second problem concerned the two peaks shown at about 6 and 7 MeV in Fig. 12.5-2. These are caused by the strong $^{19}\text{F}(p,\gamma)^{16}\text{O}$ contaminant reaction. Although it was estimated that only $\approx 0.05$ mg/cm$^2$ of $^{19}\text{F}$ contaminant was present on the 1.8 mg/cm$^2$ thick natural carbon target, this contamination created a serious problem for $E_p \approx 6$ MeV because the $^{19}\text{F}(p,\gamma)$ gamma-rays lay on top of the $\gamma_0$ peak. No target could be found which had a negligible amount of $^{19}\text{F}$ contaminant. In the first runs reported last year$^3$ this problem was not recognized; therefore it was necessary to repeat most of the excitation function while measuring a separate contaminant spectrum, using a $C_6\text{F}_6$ target, at each energy. To extract the $\gamma_0$ yield in the presence of the contaminant lines it was necessary to determine an accurate $\gamma_0$ lineshape vs energy and to perform a least squares fit to the spectrum using the $\gamma_0$ shape and the known background shape.

Figure 12.5-3 shows the preliminary results of the excitation function at 90°. The dashed line below $E_p \approx 2$ MeV is a crude drawing of the low energy excitation function known prior to these measurements. The known levels of $^{13}\text{N}$ are shown at the top. The most notable features are the strong interference effect corresponding to a $3/2^+$ state at 6.9 MeV in $^{13}\text{N}$, and a rise for $E_p \approx 7$ MeV which is the low side of the broad pygmy resonance$^4$ at about 13 MeV in $^{13}\text{N}$. There is some evidence for a resonance shown at about 8.9 MeV in $^{13}\text{N}$ ($E_p \approx 7.6$ MeV), which probably corresponds to a $1/2^-$ level seen in the $^{13}\text{C}(\gamma,\nu\gamma)$ data of Bertozzi et al.$^5$ The capture data near $E_p \approx 7.6$ MeV were rejected, as mentioned, because of the probable contamination of the $\gamma_0$ peak by the pile-up peak.

Theoretical Calculations

The coupled-channels code "JUPITER" has been modified to duplicate the calculations of Mikoshiba et al.$^1$ for protons incident on $^{12}\text{C}$ and to save the radial wave functions needed in the evaluation of the electromagnetic matrix elements. An expression for the differential capture cross-section has been derived in terms of sums of the various single particle radial matrix elements.

It is interesting to note that the strong interference effect at the $3/2^+$ level corresponds to the location of an anomaly in the $3/2^+$ elastic scattering phase shift. Figure 12.5-4 shows the experimentally determined$^4$ $3/2^+$ phase shift vs $E_p$ compared to a coupled-channels calculation which duplicates that of Mikoshiba et al.$^1$. At the energy of the anomaly the wave function of the $3/2^+$ level is dominated, according to theory$^{1,8}$ by the $(2^+ \omega s_{1/2})^{3/2^+}$ configuration.
Fig. 12.5-3. The excitation function of the differential cross section at 90° for the $^{12}$C(p,γ)$^{13}$N reaction from $E_p = 2.66$ to 8.96 MeV. The dashed line for $E_p$ below 2 MeV is a crude drawing of the low energy excitation function known prior to this work. The line at higher energies is only to guide the eye.

Fig. 12.5-4. A comparison of the measured $\frac{3}{2}^+$ elastic scattering phase shift for the $^{12}$C + p reaction to that calculated by the coupled-channel method in the same way as Mikoshiba, Terasawa, and Tanifuji. The experimental phase shifts are as given in Ref. 7.
Here is an effect in capture which clearly cannot be easily reproduced by any existing capture mechanism but may follow naturally from the coupled-channels approach.

The actual calculation of the $\text{E}1$ capture cross section as a function of energy is the next step and will be done shortly.


12.6 A Study of the Reactions $^{12}\text{C}(\alpha,\alpha'\gamma)_{15.1}$ and $^{12}\text{C}(\alpha,\alpha'\gamma)_{12.7}$

$^{10}\text{B}(\alpha,d'\gamma)_{15.1}$ and $^{12}\text{C}$

M. Hasinoff$^a$, S.T. Lim$^a$, D.F. Measday$^a$, T.J. Mulligan$^a$, and J.E. Spuller$^a$

The purpose of this experiment was to look at isospin forbidden reactions from an initial $T = 0$ state to a $T = 1$ final state and to compare them with isospin allowed reactions from an initial $T = 0$ state to a final $T = 0$ state. Specifically, we used a doubly charged alpha particle beam to bombard a $^{12}\text{C}$ and a $^{10}\text{B}$ target. Both $^{12}\text{C}$ and $^{10}\text{B}$ are even-even nuclei and have $T = 0$ ground states. The ground states of the alpha particle, $^{12}\text{C}$, and $^{10}\text{B}$ nuclei are very pure $T = 0$ states.$^1$ For the $^{12}\text{C}$ target, we measured the yield for the inelastic scattering of the alphas to the $T = 0,1^+$ state at 12.71 MeV and to the $T = 1,1^+$ state at 15.11 MeV by observing gamma decay to the ground state. In the case of the $^{10}\text{B}$ target we measured the yield of the $^{10}\text{B}(\alpha,d'\gamma)_{12.71}$ and $^{15.11})^{12}\text{C}$ reactions. The 15.11 MeV state in $^{12}\text{C}$ has 92% branching ratio for decay to the ground state by emission of a gamma ray,$^2$ while the 12.71 MeV state decays to the ground state 2.5% of the time by gamma ray emission.$^3$

The experimental procedure was to detect the gamma rays at 90 degrees to the direction of the beam. The detection of the gamma rays was done with the 10" x 10" NaI crystal of the University of British Columbia. Figure 12.6-1 is a sample spectrum from the $^{12}\text{C}$ target. The data were fitted using a standard line shape and a background approximated by a third degree polynomial. In general, the reduced chi-square were distributed about 1.4, which was acceptable, since there is some uncertainty in the tail region of the standard line and in the use of a polynomial to approximate the background. The absolute cross sections have
Fig. 12.6-1. Gamma-ray spectrum for the reaction $^{12}\text{C} + \alpha$ at a bombarding energy $E_{\alpha} = 24.45$ MeV.

Fig. 12.6-2. $90^\circ$ excitation function for $^{12}\text{C}(\alpha,\alpha'\gamma)_{15.11}$ and $^{12}\text{C}(\alpha,\alpha'\gamma)_{12.71}$ from $E_{\alpha} = 21.0$ to 27.0 MeV. The continuous lines are only to guide the eye. The stated gamma ray cross sections are good to ±50%.

an error of 50%. Most of the error comes from the extrapolation of the tail region of the standard line to zero energy and uncertainty in the target thickness. The latter will be calibrated, and we have hopes of improving the data on the tail shape to get the error of the absolute cross section down to 30%.

The yield curve for the $^{12}\text{C}(\alpha,\alpha'\gamma)_{15.11}$, Fig. 12.6-2, shows resonant processes. We observed four resonances in $^{16}\text{O}$ and saw evidence for another resonance near an excitation energy of 27.4 MeV. There appears to be little, if any, non-resonant contribution to the yield of this reaction. Table 12.6-1 lists the resonances observed in the 15.1 and 12.7 MeV gamma ray yield curves.

The yield curve to the 12.71 MeV state, also shown in Fig. 12.6-2, shows a qualitatively different structure than that seen in the 15.11 yield. Though there is still resonant structure present, the maxima are much broader and there might be some non-resonant contribution to the cross section. The $T = 0$ to $T = 0$ transition is also much stronger than the $T = 0$ to $T = 1$ transition to the 15.11 state. However, in the region of excitation 25.2 to 25.9 MeV, the 12.71 MeV yield is relatively flat, while the 15.11 yield shows a definite resonance. The ratio of $^{15.11}/^{12.71}$ is approximately 0.18. This is a fairly large fraction for an isospin forbidden reaction, and points to the importance of compound
Table 12.6-1

Summary of Resonances Observed in $^{12}\text{C}(\alpha,\alpha'\gamma_{15.11})^{12}\text{C}$

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_{\text{c.m.}}$ (keV)</th>
<th>$d\sigma(90^\circ)/d\Omega$ (µb/sr)</th>
<th>$\sigma_{\text{total}}$ (µb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.1</td>
<td>24.45</td>
<td>1000</td>
<td>2.06</td>
<td>26</td>
</tr>
<tr>
<td>24.09</td>
<td>25.20</td>
<td>450</td>
<td>8.57</td>
<td>110</td>
</tr>
<tr>
<td>24.58</td>
<td>25.59</td>
<td>450</td>
<td>6.97</td>
<td>88</td>
</tr>
<tr>
<td>25.55</td>
<td>26.30</td>
<td>450</td>
<td>5.28</td>
<td>66</td>
</tr>
</tbody>
</table>

Summary of Resonances Observed in $^{12}\text{C}(\alpha,\alpha'\gamma_{12.71})^{12}\text{C}$

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_{\text{c.m.}}$ (keV)</th>
<th>$d\sigma(90^\circ)/d\Omega$ (µb/sr)</th>
<th>$\sigma_{\text{total}}$ (µb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.0</td>
<td>23.65</td>
<td>3500</td>
<td>280</td>
<td>3500</td>
</tr>
<tr>
<td>23.4(?)</td>
<td>24.7</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>25.6</td>
<td>26.4</td>
<td>1150</td>
<td>90</td>
<td>1150</td>
</tr>
</tbody>
</table>

a. This value has been corrected for the appropriate branching ratios. There is an error of ±50%.
b. This assumes isotropy for gamma decay.

states and second order processes in introducing the Coulomb forces which can cause the breaking of the isospin rules. Other people have studied various reactions in this region of excitation in $^{16}$O. Browne et al. looked at the $^{14}$N(d,γ)$^{12}$C reaction and also saw resonant structure in the yield to the 15.11 MeV state in $^{12}$C.4

The $^{12}$C($\alpha,\alpha'\gamma_{12.71}$ and 15.11)$^{12}$C reactions are both prohibited by a "direct" reaction involving a single-scattering with a single transfer of angular momentum. This is because both the $^{12}$C and alpha have $J^\pi = 0^+$ ground states, and we looked at the excitation of $J^\pi = 1^+$ states in the target nucleus. A single transfer of orbital momentum could only go to a $J = 1$ state with negative parity. Hence the present reaction populates "unnatural parity" states. Eidson and Cramer postulate four different mechanisms which could populate these "unnatural parity" states.5 They are: 1) compound nucleus formation; 2) spin-orbit interaction; 3) non-simultaneous, multiple-phonon excitation; and 4) direct exchange processes. Since we did not take any data on the angular correlation of the gamma rays with the inelastically scattered alpha particle, it is difficult to say to what extent these various processes contributed to the reaction mechanism. However, in the
case of the yield to isospin forbidden transition to the 15.11 state, the resonant structure present indicates that compound nucleus formation is probably dominant.

The yield curves for the reactions $^{10}\text{B}(\alpha,d)\gamma^{12}\text{C}$ and $^{12}\text{C}(\alpha,\alpha')\gamma^{12}\text{C}$ are quite different. There is no resonant structure in either the 12.71 or 15.11 MeV yield curves for the $(\alpha,d\gamma)$ reactions shown in Fig. 12.6-3. The $(\alpha,d\gamma)$ reaction is relatively flat with a slowly rising yield from $\sigma_T = 2.2$ mb at 19.0 MeV to 4.2 mb at 27.0 MeV. The yield for the $(\alpha,d\gamma)$ reaction rises rapidly in the region we measured. It has an approximate value of 26 mb at 21.5 MeV and rises to 300 mb at 27.0 MeV. (We assume isotropy in calculating the total cross sections.)

In our experimental setup we could not distinguish whether the $^{10}\text{B}(\alpha,pn^{12}\text{C}$ reaction contributed to the 15.11 and 12.71 MeV yields. The threshold for the $(\alpha,pn\gamma^{12}\text{C}$ is 19.07 MeV and for the $(\alpha,pn\gamma^{15}\text{C}$ is 22.43 MeV. This latter reaction is an isospin allowed reaction since the proton and neutron could couple with the $T = 1$ state at 15.11 MeV to produce a $T = 0$ state. However, we can say that the 15.11 MeV state is definitely populated below the $(\alpha,pn\gamma^{15}\text{C}$ threshold, which would indicate a breaking of isospin. The dramatic rise in the yield of the 15.11 state occurs above the $(\alpha,pn\gamma^{15}\text{C$ threshold. This may account for the increase. One way this process could occur would be by sequential reactions

$^{10}\text{B}(\alpha,n)\text{N}^\pi$, then $\text{N}^\pi \rightarrow p + ^{12}\text{C}$

or

$^{10}\text{B}(\alpha,p)\text{C}^\pi$, then $\text{C}^\pi \rightarrow n + ^{12}\text{C}$

There are several known levels in $^{13}\text{C}$ and $^{13}\text{N}$ which could act as intermediaries for such a mechanism.

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12.7 The \(^{12}\text{C}(\alpha,\gamma_0)^{16}\text{O}\) Reaction

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The main purpose of this work is to ascertain more closely the nature of T = 0 electric quadrupole strength built on the ground state of \(^{16}\text{O}\); in particular, to locate such strength at excitation energies up to and above the Giant-Dipole Resonance (GDR). The present reaction has a number of advantages over other possible capture reactions leading into \(^{16}\text{O}\):

1) The Q-value is low (7.2 MeV), permitting the study of \(2^+\) resonances from excitation energies of about 10 MeV on upward.

2) Electric dipole (E1) radiative capture is isospin-forbidden; hence the relative strength of E2 capture should be more favorable than otherwise. In practice (see below) this effect makes E1 and E2 capture of roughly comparable strength (on the average), and interesting information is also obtained on E1 resonances.

3) Because the projectile and target are spinless, the contributions of different multipolarities may be sorted out directly from the \(\gamma\)-ray angular distributions.

To elaborate further on the last point above, the fact that both projectile and target are spinless means that only normal parity resonances (1\^, 2\^, 3\^, etc.) are formed in \(^{16}\text{O}\). Since the ground state of the residual nucleus has \(J^\pi = 0^+\), only electric multipoles E1 may be involved. In practice only E1 and E2 need be considered, as \(E_2 = 3\) and higher multipoles would be too weak to be observable here. The angular distributions reduce to their classical values: \(\sin^2 \theta\) for pure E1 capture, and \(\sin^2 2\theta\) for pure E2 capture. For a mixture of the 2 radiations (such as would occur for overlapping levels) one must square the sum of amplitudes for the two processes. Hence we may write the differential cross section

\[
\sigma(\theta) = \left| A_1 \sin \theta + e^{i \delta} A_2 \sin 2\theta \right|^2
\]

\[
= A_1^2 \sin^2 \theta + A_2^2 \sin^2 2\theta + 2A_1 A_2 \sin \theta \sin 2\theta \cos \delta
\]

where \(A_1\) and \(A_2\) are real, positive angle-independent (but energy dependent) amplitudes for E1 and E2 capture, respectively, and \(\delta\) is a real (energy dependent) relative phase. In practice one must average the above expression over the finite detector solid angle. This is easily done by writing the above expression in terms of Legendre Polynomials

\[
\sigma(\theta) = \frac{2}{3}(P_0 - P_2)A_1^2 + \frac{8}{15}(P_0 + \frac{5}{7} P_2 - \frac{12}{7} P_4)A_2^2 + \frac{8}{5}(P_1 - P_3)A_1 A_2 \cos \delta
\]

and then replacing \(P_k\) by \(Q_k P_k\) to obtain the measured angular distribution, where \(Q_k\) is the calculated attenuation coefficient of Rose. In the present case, in which the detector subtended a half-angle of 11° at the target, this replacement
changes the calculated cross section by less than 5% at the angles measured.

In the present work, we have measured the different cross section for $^{12}$C$(\alpha,\gamma)^{16}$O from $E_\alpha = 9.5$ to 27.5 MeV, at an angle $\theta_\gamma = 52^\circ$, using a 450 $\mu$g/cm$^2$ target of $^{12}$C enriched to 99.9%. This angle was chosen as a compromise between maximum yield for pure E2 radiation ($45^\circ$) and good solid angle for the large NaI detector (see Sec. 12.). Different sections of this yield curve are shown in Figs. 12.7-1 and 12.7-2. Much of the yield curve is suggestive of nearly isolated resonances, with some asymmetric shapes (such as near $E_\alpha = 12$ and 15.5 MeV) indicating the presence of interference. These measurements are consistent with the previous less detailed work of Suffert et al. 1 In order to identify the spin-parity ($1^-$ or $2^+$) of the various resonances, data at angles of $90^\circ$ and $120^\circ$ were taken at key points. Some examples are shown in Fig. 12.7-3. These 3 point angular distributions were sufficient to determine the unknown $A_1$, $A_2$, and $\cos \delta$ at the chosen energies. The spins and parities determined for each resonance in this way are shown in Figs. 12.7-1 and -2.

In addition to the $2^+$ resonances observed previously at $E_\alpha = 12.4$ and 14.8 MeV, the present work shows $2^+$ resonances at $E_\alpha = 17.3$ and 25.8 MeV. All four $2^+$ resonances have capture strengths $\Gamma_{\alpha}\gamma/\Gamma$ between about 0.5 and 1.5 eV and hence may not constitute a large fraction of the E2 $\Delta T = 0$ sum rule (which specifies a value for $\Gamma_{\alpha}\gamma/\Gamma$, equivalent to $\Gamma_{\gamma} = 50$ eV at $E_{\gamma} = 19$ MeV) unless $\Gamma_{\alpha}/\Gamma$ is substantially less than unity for some of the resonances (a likely possibility). There is thus from this work very little evidence for a giant electric quadrupole resonance with isospin zero in $^{16}$O -- the results suggest instead that the E2 $T = 0$ strength is probably spread among a number of different resonance levels.

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**Fig. 12.7-1.** The $52^\circ$ yield curve of the $^{12}$C$(\alpha,\gamma)^{16}$O reaction from $E_\alpha = 18.0$ to 27.5 MeV. The $2^+$ assignment is determined from a measured angular distribution (see text). All other resonances are $1^-$ (except, perhaps, for the 23.2 MeV resonance, for which the $J^\pi$ is presently not known). The absolute cross section is approximately 125 nb/sr per 100 count/mC.

**Fig. 12.7-2.** The $52^\circ$ yield curve of the $^{12}$C$(\alpha,\gamma)^{16}$O reaction from $E_\alpha = 9.5$ to 18.75 MeV. Here the $2^+$ resonances are indicated by arrows; other resonances are $1^-.$
A comparison of the present results with previous measurements of $^{15}\text{N}(p,\gamma_0)^{16}\text{O}$ in this energy region shows some very interesting results for the $1^-$ resonances:

1) In the region below the GDR between $E_\gamma = 17$ to 20 MeV, all four $1^-$ resonances seen in $^{15}\text{N}(p,\gamma_0)^{16}\text{O}$ are also observed in $^{12}\text{C}(\alpha,\gamma_0)^{16}\text{O}$, with roughly comparable relative intensities as seen in the different reactions. A comparison of the relative $(\alpha,\gamma_0)$ to $(p,\gamma_0)$ cross sections (based on the $(\alpha,\gamma_0)$ absolute cross section of Ref. 1) yields $\Gamma_\alpha/\Gamma_p \approx 0.02$ for these resonances, which is consistent with isospin mixing of about the same order for these states.

2) In the region of the GDR, from $E_\gamma = 20$ to 28 MeV, roughly the same number of peaks are observed in $(\alpha,\gamma_0)$ as in $(p,\gamma_0)$, but now there is no apparent correlation in energy between the peaks in the different reactions. Two possible explanations exist: a) different resonances are excited in the different reaction channels, or b) interference effects in one or both of the reactions distort the shape of the yield curve(s) and make a direct comparison difficult. Possibility (a) seems unlikely based on observation (1) above. On the other hand, the asymmetric shapes observed in $(p,\gamma_0)$ long ago suggested the likelihood of interference in this reaction. The average cross section ratio of $(p,\gamma_0)$ to $(\alpha,\gamma_0)$ is roughly 35:1 in this range, compared with about 50:1 for the resonances between $E_\gamma = 17$ to 20 MeV.

An attempt is underway to try to understand the structure (shape) in the giant-dipole photoabsorption cross section (which is reflected in the $(p,\gamma_0)$ yield curve) in terms of the $1^-$ resonances observed here in the $(\alpha,\gamma_0)$ reaction, by taking interference into account. Further, more detailed comparisons are under way between $(\alpha,\gamma_0)$ and other reaction channels. In addition, further measurements are planned to complete the yield curve for energies below $E_\alpha = 10$ MeV and to add more angular distribution measurements.

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Fig. 12.7-3. Some representative angular distribution measurements. A maximum at 90° corresponds to predominant E1 radiation, while a minimum at 90° corresponds to predominant E2 radiation; other examples constitute mixtures.

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12.8 Radiative Proton Capture into the Giant Dipole Resonance of $^{29}$P

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We have undertaken preliminary experiments on the reaction $^{28}$Si($p$,γ)$^{29}$P, by bombarding a natural silicon target (92% $^{28}$Si) with protons in the energy range 10 to 19.4 MeV. The target thickness was ≈ 850 μg/cm² (~ 20 keV) but lack of time limited the study of the excitation function to steps of 100 to 200 keV. The gamma-rays were detected in the 10" × 10" NaI spectrometer of the University of British Columbia, placed at 90° to the beam direction. The energy resolution obtained under normal working conditions was between 4% and 5%, which was more than sufficient to separate the gamma-rays leading to the ground-state from those leading to the first excited state of $^{29}$P at 1.78 MeV.

A typical spectrum, taken at $E_p = 19.2$ MeV, is illustrated in Fig. 12.8-1. The left hand side of the figure shows the high energy portion of the gamma-ray

![Image of gamma-ray spectrum](image)

**Fig. 12.8-1.** The left side of the figure shows the high energy portion of the gamma-ray spectrum following bombardment of natural Si with 19.2 MeV protons. The right hand side displays the region around the γ₀ peak in greater detail.
spectrum. The peaks marked $Y_0Y_1$ etc. are the capture gamma-rays leading to the ground state, the first excited state, etc. of $^{29}\text{P}$, respectively. The 15.11 MeV gamma-ray comes from inelastic proton scattering from the carbon buildup on the surface of the target. The right hand side is a detail of the $Y_0$ part of the spectrum. There is a significant background on the high energy side of the peak which is attributed mainly to capture gamma-rays from the other silicon isotopes which have higher Q-values, viz. $^{28}\text{Si}$, 2.74 MeV; $^{29}\text{Si}$, 5.59 MeV; $^{30}\text{Si}$, 7.29 MeV.

A preliminary yield curve was obtained by summing the counts within the window as marked in Fig. 12.8-1 after subtracting the background given by the dashed line. The resulting yield curve is shown in Fig. 12.8-2. Significant structure is observed consistent with neighboring nuclei in the mass region. There are no other data on the capture reaction, but some high-energy levels in $^{29}\text{P}$ are known from other reactions and these are marked as arrows at the top of the yield curve.

The study will continue using an isotopically pure target and with improved liquid nitrogen traps in the beam line. These two changes will reduce the background under the $Y_0$ peak. A gain stabilizer has recently been added to the NaI spectrometer and improved energy resolution is expected. The final experiment will be performed with finer steps in the yield curve in order to obtain further information about the sharp structure which is clearly indicated in the present data.

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1. Section 4.2 of this Report.

12.9 $^{39}\text{K}(p,\gamma)^{40}\text{Ca}$ and the Search for $\Delta T = 2$ Electromagnetic Transitions

E.G. Adelberger, M.D. Cooper, R.E. Marrs, and K.A. Snover

Our search for violations of the electromagnetic isospin selection rule, that $\Delta T = 0$ or $\pm 1$, has continued.\textsuperscript{1} Experimental limits\textsuperscript{2} on the intensity of $\gamma$ transitions between $T = 2$ and $T = 0$ states presently exist only for $E2$ transitions. We are attempting to locate dipole transitions since they are inherently stronger and should therefore provide a more sensitive test of the existence of $\Delta T = 2$ currents. The lowest $2^+$, $T = 2$ state in $^{40}\text{Ca}$ has been chosen for study both because spin and parity conservation permit dipole decays to the low lying $T = 0$ states, and because penetrabilities for the particle decay channels
Fig. 12.9-1. The $^{39}$K(p, p') excitation function at 165°(lab) taken with a KF target on a carbon backing.

suggest that most of the decay strength could go to the $^{39}$K ground-state-plus-proton channel.

Since this T = 2 state in $^{40}$Ca has not previously been seen, we have attempted to locate it by measuring $^{39}$K(p, p') and $^{39}$K(p, γ) excitation functions over a range of proton energies corresponding to the expected location of this state. Figure 12.9-1 shows the elastic proton excitation function at an angle of 165°(lab).

The observation of the γ-rays is complicated by the following constraints on the choice of targets: (1) To obtain a high (p, γ) yield, the target must consist either of metallic potassium or a potassium compound containing only low Z elements. (2) Both the target itself and the target backing must be free of materials which produce large numbers of γ-rays, or γ-rays of energy comparable to the energies of the γ-rays expected from the T = 2 state in $^{40}$Ca. These requirements prevented use of the KF target used for the particle excitation functions to obtain the γ-ray data. Instead it was decided to make the targets from metallic potassium and accordingly a device was built to transfer the targets in vacuum from the evaporator to the scattering chamber. Backings of carbon, nickel and platinum have been tried, but only the platinum backing has been satisfactory.

The γ-ray yield has been observed at 90° with both the "9.3%" Ga(Li) detector and the 10" × 10" NaI detector. It was hoped that the superior resolution
Fig. 12.9-2. The NaI \( \gamma \)-ray spectrum at 5.254 MeV. Transitions to the first several excited states of \(^{40}\text{Ca}\) are visible in addition to the ground state transition.

of the Ge(Li) detector would compensate for its lower efficiency. However, the Doppler broadening of the \( \gamma \)-ray lines from \(^{40}\text{Ca}\) and the presence of a background have made it difficult to see any but the strongest \( \gamma \)-rays with the Ge(Li) detector.

Initially, there was a problem with a large background in the NaI due to neutrons. This was solved by bunching the proton beam and requiring a time coincidence between the detected \( \gamma \)-ray and the proton bunch. Figure 12.9-2 shows a \( \gamma \)-ray spectrum taken at a proton energy where \( \gamma_0 \) resonates; this resonance is obviously not the \( T = 2 \) state.

Completion of the excitation function is still in progress.
12.10 Explaining the Regular Features of Fast Nucleon Capture Angular Distributions

I. Halpern and R. Heffner

The angular distributions, $W(\theta)$, of high energy photons resulting from the capture of a proton or neutron to some specific low-lying state in a residual nucleus are customarily expressed in the form:

$$ W(\theta) \sim A_0 [1 + \sum_{n=1}^{\infty} a_n P_n (\cos \theta)]. $$

It is found that the measured coefficients, $a_n$, show a persistent stability as the bombarding energy is varied.\(^1\) That is, despite some fluctuations in these quantities over small energy intervals, their averages over moderate intervals are observed to change only slowly with energy. This suggests that these averages must be simply related to the dominant mechanisms involved in nucleon capture and should therefore be explainable in terms of these mechanisms in a straightforward way.

In recent years it has become increasingly apparent that the mean magnitudes and energy dependences of nucleon capture cross-sections can be accounted for, throughout the periodic table, in terms of the so-called semi-direct capture theory.\(^2\) In this theory the three main amplitudes for radiative capture are associated with radiations from i) the incident nucleon as it accelerates in the optical potential of the target, ii) the nuclear recoil associated with this acceleration and iii) the electric dipole oscillation of the target as a whole which is induced by the projectile. The first two amplitudes are called direct-radiation components and vary very slowly with energy. The third, the polarization component, flares up at excitation energies corresponding to the giant dipole resonance where it becomes responsible for about 90% of the observed cross-section.

In what follows we briefly outline how the values, energy dependences and correlations of the $a_n$ coefficients can be understood in terms of the foregoing three amplitudes.\(^3\) Most attempts to understand capture angular distributions have been carried out with reference to specific nuclei ($^{16}O$ seems to be a favorite\(^4\)). Such attempts naturally involve the specific structural properties of the nuclei in question. Since the exact locations of nuclear states or configurations may be somewhat irrelevant when several broad states are coherently excited (as they are in capture) such calculations may tend to obscure the simplest most common features of the capture process. A description involving only a limited number of degrees of freedom (but the right ones) is likely, in this
case, to be more illuminating.

The general form of the angular distribution of the chief radiation component from a nucleus, the dipole component, is \( a + b \sin^2 \theta \). This form refers to a system in which the radiating charges are moving slowly. Where they are moving with a speed \( 3c \) in the direction \( \theta = 0 \), it is easy to show that in the classical limit the corresponding distribution becomes

\[
\frac{a}{(1 - \beta \cos \theta)^2} + \frac{b \sin^2 \theta}{(1 - \beta \cos \theta)^2}.
\]

The factors in the denominator fold the distributions forward in the laboratory system. If this folded distribution is expressed in the standard form of Eq. (1) to lowest order in \( \beta \), one finds that

\[
a_1 = \frac{2}{3} \frac{1 + 4/5(b/a)}{1 + 2/3(b/a)}; \quad a_2 = -\frac{2/3(b/a)}{1 + 2/3(b/a)}; \quad a_3 = -\frac{8/5(b/a)}{1 + 2/3(b/a)}.
\]

(2)

In an extreme classical model for capture, the ratio \( b/a \) depends on the impact parameter at which capture takes place. For head-on collisions, for example, \( b/a \) is infinite whereas for collisions at the edge of the nucleus, \( b/a = -1/2 \). More generally \( b/a = (y_{\text{m}}/y)^2 - 3/2 \), where \( y = 1/2y_{\text{m}} \) gives the ratio of the mean impact parameter in the capture at a given energy to the maximum possible value, i.e., the value at the nuclear edge. In terms of the ratio \( y \) the lowest coefficients \( a_n \) become simply

\[
a_1 = 2.48 \left(1 - \frac{y^2}{4}\right); \quad a_2 = 3/2 \left(y^2 - 1\right), \quad a_3 = 2.48(3/2 y^2 - 1).
\]

(2a)

Of the three amplitudes mentioned above only that associated with the incident proton will give rise to non-zero \( a_1 \) or \( a_3 \) coefficients. The other two amplitudes are due to heavy radiators and \( \beta \) is consequently negligible for them at the time of radiation. The specific forms of Eqs. 2a are strictly classical and should be taken with a grain of salt especially for the low quantum numbers often encountered in radiative capture. Yet, as we shall see, they can serve as a reasonable starting point for understanding the regularities that have been observed for the properties of the coefficients \( a_n \). We turn now to some of the implications of Eqs. 2a for the \( a_n \) coefficients with brief comments about the extent of the agreement of these implications with actual experimental observations.

A. **Sign and magnitude of \( a_1 \) in proton capture:** This coefficient is expected to be small at giant resonance energies where the polarization amplitude, (iii), dominates and to be necessarily positive and rising at higher energies. It should approach values of 4.8, i.e., twice the value appearing in Eq. 2a. All of these features appear to be in good accord with experiment.

B. **Sign and magnitude of \( a_2 \) in proton capture:** According to Eq. 2a, the coefficient \( a_2 \) should be large and negative for captures into orbits where the
angular momentum \( l \) is small compared with the maximum value, \( l_m \), which is available in the lowest non-empty oscillator shell of the target nucleus. The value of \( a_2 \) should approach \(+ l/2 \) as \( l \) approaches \( l_m \). Most of the experimental values of \( a_2 \) refer to nuclei so light that the classical assumptions behind Eq. 2a are most questionable. The few measurements available for sd shell, \( f \) shell and heavier nuclei appear to be qualitatively in agreement with our expectations for both the sign and size of \( a_2 \).

C. Correlations among \( a_1, a_2 \) and \( a_3 \). These correlations are best explored at bombarding energies above the giant resonance region to avoid overshadowing of the direct amplitudes by the polarization amplitude. Then one can expect, according to Eq. 2a, that \( a_3 = (2.48) a_2 \) and that \( a_3 = a_1 (5/4 \gamma^2 - 1) \). The only available post-giant-resonance capture measurement involving all three coefficients appears to be that of O'Connell for \( {^15}_N(p, \gamma 0) \). At incident proton energies of 16 to 18 MeV the average values of his observations are: \( a_1 = 0.35, a_2 = -0.6 \) and \( a_3 = -0.2 \). These values are not inconsistent with the relations just given using reasonable values for \( \beta \) and \( \gamma \). It would be of considerable interest to make a systematic study of the values of \( a_1, a_2 \) and \( a_3 \) at post-giant resonance especially for heavier nuclei.

D. The correlation of \( a_1 \) with \( A_0 \). According to the classical model for \( W(\theta) \) the \( a_1 \) and \( a_3 \) coefficients arise entirely from kinematic effects associated with the transformation of the radiation pattern of the incident proton into the laboratory coordinate system. The proton radiation amplitude is a direct amplitude and varies very slowly with bombarding energy. (This is also true of the amplitudes we have numbered (ii) and (iii).) Those radiation amplitudes which vary more rapidly with energy and are responsible for the intermediate and fine structure in the capture cross-section are presumably associated with doorways and compound nuclear states. Since \( a_1 \) measures the ratio of the cos \( \theta \) term in \( W(\theta) \) to the total angle-integrated cross-section, it is clear that when this cross-section has an upward fluctuation, \( a_1 \) should decrease and when the cross-section goes down, \( a_1 \) should go up. The clearest example of this kind of anti-correlation between \( a_1 \) and \( A_0 \) appears in the work of Kuan (see Fig. 12.10-1).

To summarize: According to the foregoing analysis, the main features of \( W(\theta) \) in proton radiative capture can be understood in terms of the direct amplitude associated with the proton -- including the quadrupole part of this amplitude. That is not to say that there cannot be any specifically nuclear con-

Fig. 12.10-1. There is an anticorrelation between the \( a_1 \) coefficient in the angular distribution for \( {^15}_N(p, \gamma 0) \) and the integrated cross-section for the reaction. This is taken as evidence for the constancy as a function of incident energy of the amplitude associated with the cos \( \theta \) term in the distribution.
tributions to the quadrupole amplitude. However, if there are, they would tend
to be masked by the direct effects in proton capture. Since the direct quadru-
pole amplitude happens to be negligible when neutrons instead of protons are
being captured, it is clear that it is better to look for collective nuclear
oscillations (e.g., E2 giant resonances) using neutrons rather than protons.

1. R.G. Allas, S.S. Hanna, L. Meyer-Schützmeister, R.E. Segel, P.P. Singh,
3. These subjects are presented in greater detail in the Proceedings of the
International Conference on Photonuclear Reactions which was held at
Asilomar in March 1973 (to be published).
5. Relations between the quantal and classical calculations of the direct
radiation amplitudes are discussed in more detail in Ref. 3.
6. This point was already made in the 1971 Progress Report of the Nuclear
Physics Laboratory, p. 173.
14N H.M. Kuan \textit{et al}.,(\textit{ibid}) and K. Snover (private communication).
15N W.J. O'Connell (Stanford thesis 1969) and K. Snover (private com-
munication).

12.11 Preliminary Investigation of Proton Capture Reactions in \textsuperscript{45}Sc, \textsuperscript{51}V, \textsuperscript{93}Nb
and in

K. Ebisawa, I. Halpern, and D.L. Johnson

It is shown in Sec. 12.10 that many features of proton capture angular
distributions can be at least qualitatively understood in terms of a classical
description of the radiative capture process. One implication of this descrip-
tion, insufficiently tested, concerns the value of \(a_2\) in the expression
\(W(\theta) = A_0[1 + \sum_{n=1}^{\infty} a_n P_n(\cos \theta)]\) for the capture angular distribution. It is that \(a_2\)
(which is generally negative for capture in the lightest elements) should become
positive for heavy element captures into the radially nodeless shell model orbits
(i.e., into the available orbits of largest angular momentum).

We have made a single run on several high spin odd-Z targets in order to
estimate required intensities for angular distribution measurements to the ground
states of the residual even-even nuclei. The emitted \(\gamma\)-rays were detected at 90°
to the beam using the U.B.C. 25 cm \times 25 cm NaI crystal. Using the \(^{11}B(p,\gamma)\)
reaction, the energy resolution (FWHM) of this crystal had been shown to be 3.3\%for 23.4 MeV photons. Such good energy resolution is required in studies of
heavier targets in order to separate the ground state from excited states.
With target thicknesses of a few mg/cm$^2$ one observes fewer than 100 counts per hour with the present counter geometry. The observed rates correspond to cross-sections of 0.6, 0.4 and 0.2 mb/sr for $^{45}$Sc, $^{51}$V and $^{99}$Nb respectively. For In the cross-section has an upper limit of 0.1 mb/sr. Even though $a_2$ coefficients can be measured with relatively poor statistics, it will be necessary to modify our detection arrangement to increase counting rates in order to measure angular distributions.

In the meantime we have learned of some measurements by Diener et al.\textsuperscript{1} which show that $a_2$ does, as expected, become positive for captures to $f_{7/2}$ orbits for odd Z targets in the $f_{7/2}$ shell. For both $^{51}$V(p,$\gamma_0$) and $^{59}$Co(p,$\gamma_0$) they find average values of $\gamma+0.11$ for $a_2$ in an excitation range a few MeV wide near 18 MeV.

13. FISSION AND FISSION ISOMERS

13.1 Search for Conversion Electrons from the Decay of Excited States in the Secondary Minimum of $^{238}\text{U}$

R. Heffner, J. Pedersen, P.A. Russo, G. Sletten, and H. Swanson

The investigation of transition energies from rotational band states in the shape isomer potential of the actinide nuclei, discussed in last year's Annual Report, has been continued. Electrons from the highly internally converted rotational transitions are bent under the influence of a magnetic field into a Si(Li) counter where they are detected in delayed coincidence with the fission fragments, also detected with a solid state counter system. The essential details of the electron–fission fragment counter system have been reported earlier and are shown in Fig. 13.1-1.

![Diagram](image)

Fig. 13.1-1. A top view of the experimental setup bounded by the magnetic pole face. Only one of the three fission detectors is displayed. Shown are the trajectories of a high energy electron which is detected and of a low energy electron which passes into the gap. The inset shows the fission fragment detector as seen looking upstream.

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Data was taken with the system described in Ref. 1 for the reaction \(^{238}\text{U}(d,pn)^{236}\text{Pu}\) using 19 MeV incident energy deuterons. Electrons in delayed time coincidence were observed as verified by the time spectrum for events in the electron and fission counters (Fig. 13.1-2). The coincidence energy spectrum contained peaks tentatively identified with the L and MN conversion electron transitions from the \(8^+ \rightarrow 6^+\) and \(6^+ \rightarrow 4^+\) rotational band transitions and the MN conversion line from the \(4^+ \rightarrow 2^+\) transition. This tentative assignment was based upon the known L-MN energy spacing in \(^{238}\text{U}\) and the observed relative intensities of the peaks, as well as corroborative evidence for the existence of the rotational transitions in the neighboring even-even shape isomer, \(^{240}\text{Pu}\).

We note here that the electron detector energy resolution for this data was about 5 keV FWHM. Consequently the L\(_{\pi1}\) and L\(_{\pi11}\) as well as the M\(_{\pi11}\)-M\(_{\pi11}\) and N\(_{\pi11}\)-N\(_{\pi11}\) conversion transitions were not resolved. Thus the notation L and MN above refers to these weighted averages.

It was found, however, that the measured transition energies were inconsistent with the adiabatic rotor model which would predict the relation \(E(I) = AI(I + 1) - BI^2(I + 1)^2\), where I is the spin of the emitting state and A and B are positive constants. This discrepancy was eventually traced to a buildup of hydrocarbons on the face of the liquid-nitrogen cooled electron detectors causing a degradation of the incident electron energies and therefore a non-linear energy spectrum. Consequently, the scattering chamber vacuum system was overhauled and the chamber is now evacuated for several days prior to cooling the detector, thus reducing the buildup to a tolerable level. To monitor the energy calibration as a function of time, a device was built which would rotate a \(^{103}\text{Rh}\) target in and out of the beam. Deuteron bombardment of this target produces short lived, high yield conversion electron lines with energies 16.8, 36.9, 39.5, 54.4, 74.5, and 77.1 keV. The energy calibration is checked every few hours.

To calibrate and to monitor the time spectrum, a weak \(^{241}\text{Am}\) source is placed on the catcher foil facing "upstream" and is left in place throughout the duration of the run. The Am source produces electrons with a 67 nanosec half life in coincidence with alpha particles and consequently can be used to set up and check the electronics system. The source is weak enough so that its contribution to the final coincidence spectrum is negligible.

Several major improvements were made to the system in the last year. The data described above were taken with laboratory-built Si(Li) electron detectors. After failing to consistently obtain better resolution than about 4 keV FWHM for electrons in the 100 keV energy range, it was decided to try to purchase custom made detectors commercially. A 300 mm\(^2\), 3 mm thick Si(Li) detector was purchased from Kevex Corporation. The system resolution (detector, preamp and amplifier)
at 30,000 counts/sec is now about 1.8 keV FWHM. The preamp for this data is
 capacitively coupled to the detector. A direct coupling scheme is being con-
 sidered.

The fission-fragment detector system was also modified. The original
fission fragment detectors were about 200-300 micron thick Si(Li) detectors,
again laboratory-built. These counters have been changed to thin (about 60
microns) surface barrier detectors. Furthermore, 400 μg/cm² thick nickel foils
were mounted to cover the surface of these detectors to suppress the electron
background below about 10 keV. It was found that without these protection foils
the detectors could break down because of the intense electron bombardment.

The shape of the electromagnet pole faces was also varied to try to maxi-
mize the electron solid angle. The first pole faces tried were parallel plates
producing a uniform "vertical" magnetic field (out of the paper in Fig. 13.1-1). The
solid angle obtained with this configuration was about 5% of 4π steradians over
the energy region of 20 to 100 keV. Conically shaped pole tips were then tried
in an attempt to increase the solid angle by providing vertical focusing. It
was determined that the conically shaped poles could increase the solid angle by
about 50%; however, the dynamic range for this high solid angle was greatly re-
duced compared to the parallel plate poles. Furthermore, the low energy cutoff
produced by the action of the field, crucial to the moderation of the electron
counting rate, was not as sharp for the conical shapes. Consequently, the para-
allel plate poles were adopted.

A single run using the new counter system has been completed. A 5 μg/cm²
236U target was bombarded with about 40 nanoamps of 19 MeV deuterons producing a
counting rate of about 30 K/sec in the electron detector. About 4300 delayed
fission events were collected resulting in nearly 200 coincidence events which
satisfied the proper time and energy criteria. At the time of this report the
data have not been completely analyzed and no definitive statement can be made
regarding the transition energies observed.

1. Nuclear Physics Laboratory Annual Report, University of Washington (1972),
   pp. 21, 152.
   (1972).

13.2 Gamma Branch of the 238U Shape Isomer


Delayed fission measurements¹ have established half lives and fission
isomer ratios for the even-even shape isomers of uranium. These same results
predict a gamma branch strong enough to compete effectively with delayed fission
in the process of shape isomer de-excitation for the even-even uranium isotopes.
It has been the object of this investigation to identify and measure the gamma
branch of the 195 nsec 238U shape isomer. A gamma ray of 2 to 3 MeV with a 195
nsec half life is expected from this mode of decay. The anticipated cross
section of the gamma branch of $^{238}\text{U}$ produced by the $^{238}\text{U}(d,pn)$ reaction with 18 MeV deuterons is 50 to 100 b. A previous report\textsuperscript{2} justifies these details and provides a description of the experimental situation.

A critical modification of the data collection procedure has achieved an increased sensitivity in the experiment. Both time and energy information associated with delayed gamma rays is stored in the computer event by event. The computer also accumulates a 4096 channel energy spectrum and a 256 channel time spectrum which are used for monitoring purposes. The 4000 word buffer which accumulates the single-event data is written on tape automatically when full. This method of data storage permits selection of the optimum time region after the beam burst for analysis of delayed activity with a particular half life. Figure 13.2-1 shows the time spectrum for all gamma rays with energies between 1.2 and 3.7 MeV. (Raising the energy discriminator to 2.5 MeV does not alter this picture qualitatively.) The ideal region for analysis in this case begins about 200 nsec from the beam burst edge. In practice, the prompt events are gated out of the data sent to the computer to minimize dead time in event storage and computer tape writing. Prompt time spectra are accumulated periodically for monitoring purposes. The modified data collection procedure is coupled with a program for off line data analysis in which software windows are set on any region of the 256 channel time array or the 4096 channel energy array. The corresponding (energy or time) spectrum of events is generated from the buffer data.

Zero shifts and fractional percent gain shifts in the 4000 channel energy spectrum during the typical five-day data collection periods have inspired some changes in experimental procedure. A signal from a temperature-stable pulser is fed to the preamp to produce a peak in the energy spectrum near channel 4000 (corresponding to approximately 3.8 MeV). A $^{133}\text{Ba}$ source mounted near the Ge(Li) detector throughout the experiment produced several lines (below 0.4 MeV) in the low-energy end of the spectrum. The relative shifts in the pulser peak and the low energy lines distinguish gain shifts from zero shifts. Several strong lines near 1 MeV in the energy spectrum, some of which are associated with normal isomeric states in fission fragments, have also been used to monitor the gain. Based on the magnitudes of the shifts, the data is corrected in blocks corresponding to one-hour periods of collection time.

The experimental technique is sensitive to cross sections greater than or equal to 50 $\mu$b for a 200 nsec decay. This is improved by a factor of two with background subtraction. An average, long-lived background of events occurring late in the time spectrum is subtracted from energy spectra associated with
events occurring in early time regions in which 200 nsec lifetimes can be observed. As applied to the present data, the background subtraction eliminates activities with half lives greater than 2 µsec and greatly reduces activities with half lives greater than 0.5 and less than 2 µsec. Background subtraction has been applied to all of the data discussed below.

Data taken with 18 MeV deuterons on $^{238}$U have been compared with 13 MeV proton data collected under the same experimental conditions with an equivalent number of prompt events. $^{237}$Np or $^{237}$Np can be produced by both experiments in the compound reactions $^{238}$U(d,3n) and $^{238}$U(p,2n). Only the 18 MeV deuteron experiment can populate the $^{238}$U shape isomer. Although a large gamma branch is predicted for 40 nsec $^{237}$Np, there is no reason to expect a decay strength concentrated in any one transition in an odd nucleus excited to 2 or 3 MeV. Therefore, gamma lines common to the two experiments are probably associated with fission fragments. An additional comparison can be made with data obtained in an experiment similar to the present investigation where $^{235}$U is bombarded with 13 MeV-deuterons. Gamma lines common to this experiment and either of the two present experiments must be associated with background, probably from fission fragments.

Data has been analyzed for gamma energies between 1.2 and 3.6 MeV. (Data for lower energy gamma rays is still to be analyzed.) Of the 39 lines appearing in the subtracted spectra obtained from the 18 MeV deuteron data, 21 are observed in the data from $^{238}$U + 13 MeV p or $^{235}$U + 13 MeV d. Based on half life determinations, all but one of the remaining lines can be eliminated. The single high energy line which remains appears in a portion of the energy spectrum shown in Fig. 13.2-2. The energy of the 2.514 MeV is consistent with a transition from the 0+ isomeric level to the first excited 2+ state at 0.045 MeV in normally deformed $^{238}$U. This leads to an excitation of 2.559 MeV for the $^{238}$U shape isomer. The cross section for this line, assuming a 195 nsec half life, is 80±0 µb which is within the range predicted from the measured fission isomer ratios. The time decay of the same line is shown in Fig. 13.2-3. The fitted half life of 191±4 nsec is in good agreement with the 195±13 nsec half life of $^{239m}$U obtained from delayed fission measurements.$^1$

The second excited state of normally deformed $^{238}$U is a 1- state at 0.680 MeV. A line at 1.879 MeV corresponding to the transition from the 2.559 MeV 0+ (isomeric) level to this 1- state appears in lower yield. The measured cross section for this line is 30±12 µb based on a half life of 195 nsec. This represents the experimental limit of sensitivity. Although the uncertainties are very large, the time decay indicates a half life which is not inconsistent with 195 nsec. Little information is available on the relative El and E2 strengths in this region, but extrapolation of relative strengths obtained from neutron capture data in higher energy regions and radioactive decay data at lower energies suggests that equivalent E2 and El strengths near 2 MeV is not unreasonable.

The absolute cross section for isomeric fission of $^{238m}$U produced by the $^{238}$U(d,pn) reaction with 18 MeV deuterons is 7 µb.$^2$ If 80 µb represents the total strength of the gamma branch for $^{238}$U produced by the same reaction, then
Fig. 13.2-2. Energy spectrum obtained from $^{238}\text{U} + 18 \text{ MeV d}$ experiment. Background is not subtracted.

the ratio of strengths, $\Gamma_i^\gamma/\Gamma_i^f$, is approximately 1.1. This can be considered a lower limit since gamma branching to higher excited states may be significant but too divided among these states to be observed. Theoretical estimates for $\Gamma_i^\gamma/\Gamma_i^f$ predict $^4,\, ^5$ that the inner barrier must be $10^5$ to $10^7$ times more penetrable than the outer barrier for comparable strengths in the two branches. For $\Gamma_i^\gamma/\Gamma_i^f = 10$, these range limits become $10^6$ to $10^8$. The experimental value of $E_{II}$, the isomer excitation energy, can be used to calculate $P_A/P_B$ for parabolic barriers from the expression

$$P_A/P_B = \exp \left( 2 \cdot \frac{E_B - E_{II}}{E_B} - \frac{E_A - E_{II}}{E_A} \right).$$

Here $E_A$ and $E_B$ are the heights of the inner and outer barriers and $\hbar \omega_A$ and $\hbar \omega_B$
are the corresponding barrier curvature parameters. Using the parameters, $E_A = 6.162$ MeV, $E_B = 5.982$ MeV, $\hbar\omega_A = 0.924$ MeV and $\hbar\omega_B = 0.531$ MeV obtained from fits to $^{238}\text{U}(t,\text{pf})$ excitation functions, and $E_{\Pi} = 2.559$ MeV obtained in this investigation, the value of $F_A/F_B$ is $8.8 \times 10^5$, consistent with the theoretical predictions.

4. J.R. Nix and G. Walker, Nucl. Phys. Fig. 13.2-3. Time spectrum of the 2.514 MeV line (in Fig. 13.2-2). Solid line is the least squares fit to the data.
6. B.B. Back et al., private communication.

13.3 Relative Excitations of the $^{237}$Pu Shape Isomers

R. Methot, Jr., P.A. Russo, G. Sletten, and R. Vandenbosch

$^{237}$Pu has been shown to exhibit two isomeric states, with half-lives 82 and 1120 nsec respectively, both of which decay directly or indirectly by spontaneous fission. These two isomeric states are attributed to different single particle states at the deformation of the shape-isomeric potential well. It has been shown that the shorter-lived isomeric state has the lower spin. The purpose of the present experiment is to determine which isomer has the lower excitation energy.

To do this we have measured the excitation functions of the two isomers for the $^{235}\text{U}(\alpha,2n)^{237}\text{Pu}$ reaction, and extracted the isomer production thresholds from these. The yields of the two isomers were measured by a recoil fission in flight method using plastic track detectors. Details of the experimental technique are given in Ref. 2.

The distribution of tracks along the recoil path was converted into a decay curve assuming full momentum transfer to the recoiling compound nucleus. The decay curves were resolved by a least-squares analysis into 82 and 1120 nsec half-life components.

Data has been taken for incident $\alpha$ energies ranging from 22.0 to 25.5 MeV, and at the lowest energies repeated measurements were done. The yields were
divided by the number of prompt fissions to remove the effect of the Coulomb barrier. The resulting excitation functions are shown in Fig. 13.3-1. Only relative values of the isomer to prompt fission ratios are given as the absolute delayed-fission detection efficiency, common to both components, is not well known.

The solid curves in Fig. 13.3-1 are fits of a modified Jackson neutron evaporation model to the data. As employed here the model has four parameters: the isomer energy $E_i$, the outer fission barrier $E_B$, the nuclear temperature $T$, and an adjustable normalization constant. For each individual fit $T$ is kept constant and a search routine adjusts the other parameters for a minimum value of chi squared.

The best fits were obtained at nuclear temperatures of 0.4-0.5 MeV with $T = 0.5$ MeV as the best common value for the two excitation functions.

The final values are:

$E_i(1120$ nsec) = $3.45 \pm 0.10$ MeV,

$E_i(82$ nsec) = $3.10 \pm 0.15$ MeV, and

$E_B = 4.8 \pm 0.4$ MeV. This yields a relative excitation energy for the two states of $0.35 \pm 0.12$ MeV. Perturbations due to spin fractionation with increasing angular momentum reduces this difference to $0.30 \pm 0.12$ MeV. This effect has been calculated by a statistical model code similar to that employed in Ref. 1.

According to Ref. 1 the most likely spin assignments for the two isomers are $11/2$ for the 1120 nsec state and $5/2$ for the 82 nsec state. This can be compared to the calculations of single particle diagrams by Mosel et al. where the orbitals close to the Fermi surface at the isomer deformation for a nucleus with 143 neutrons are $11/2^+[615]$, $5/2^+[862]$, and $3/2^-[512]$. As a consequence of the stronger pairing interaction for a pair of nucleons in a high-spin orbital than in a low spin orbital it is most likely that the $11/2^+[615]$ orbital is not the ground state in the isomer well, but rather appears as an excited state. This is clearly demonstrated in several rare earth nuclei where the $11/2^-[505]$ orbital comes very close to the Fermi surface, but never becomes the ground state.

Fig. 13.3-1. Observed ratio of isomeric to prompt fission as a function of alpha particle bombarding energy for the two fission isomers of $237$Pu. The solid curves represent fits to the data using a modified Jackson neutron evaporation model.
The theoretical findings combined with the isomer ratio results of Ref. 1 agree well with the result of the present investigation. Although the spin assignments are far from being established one can tentatively conclude that the 1120 nsec isomer might be an $I = 11/2$ excited state in the isomer well, about 300 keV over the 82 nsec lowest state.

Whether the 1120 nsec isomer decays by spontaneous fission directly is not clear. The half-life is not in conflict with a $K$ forbidden $\gamma$-transition to a rotational band built on the isomer well ground state. Thus the observed delayed fissions may be associated either with fission direct from the long-lived isomer state or with fission of the short-lived state populated by gamma decay of the long-lived isomeric state.


13.4 Microscopic Calculation of Fission Fragment Anisotropies for Nuclei Exhibiting a Double Barrier

R. Vandenbosch

At moderate excitation energies where statistical considerations prevail, fission fragment angular distributions give information about the effective moment of inertia and the nuclear temperature of the saddlepoint configuration. For heavier nuclei the effective moments of inertia deduced from fragment anisotropies differ from those expected on the basis of the generally used liquid drop model. A possible explanation for this discrepancy may lie in the fact that shell effects result in a double-humped fission barrier, with the resulting saddle-points having different deformations than that of the liquid drop saddle-point configuration. Shell effects also influence the relationship between the excitation energy and the nuclear temperature.

We have performed a microscopic calculation of the quantity $K_0^2$ characterizing the fragment anisotropy. The results of the calculations for three different deformations are compared with experimental values in Fig. 13.4-1. Two of the deformations chosen correspond to the inner ($\epsilon = 0.44$) and outer ($\epsilon = 0.66$) barriers of plutonium. Also shown are the $K_0^2$ values for the deformation ($\epsilon = 0.76$) of the liquid drop barrier. It is seen that the anisotropy appears to be determined by the outer barrier for excitation energies up to about 30 MeV.

There are a number of reasons why the outer barrier may be determinative in establishing the anisotropies even for nuclei such as the plutonium isotopes where the available evidence suggests that the inner barrier is higher than the outer barrier. As one passes from the first barrier to the second barrier the level density becomes quite high at the deformation corresponding to the shape isomer. There is evidence from the widths of "vibrational" resonances that there
Fig. 13.4-1. The calculated dependence of $K_0^2$ on excitation energy for the three deformations corresponding to the inner ($\varepsilon = 0.44$), liquid drop ($\varepsilon = 0.76$), and outer ($\varepsilon = 0.86$) barriers of $^{242}$Pu. Pairing effects have been included. The low energy n,f data are for $^{234}$U (crosses) and $^{240}$Pu (circles) and is taken from Refs. 2 and 3. The high energy data are for $^{237}$Pu and are taken from Ref. 1.

is some mixing of these more complicated configurations with the fission degree of freedom.$^{1,5}$ It is not clear however whether this "damping" of the fission mode is accompanied by K-mixing. It is possible that there will be sufficient Coriolis coupling to these states so that the K distribution established at the first saddle will not be preserved. The K distribution can then be reestablished at the second barrier, beyond which the descent to scission proceeds sufficiently fast that the K distribution characteristic of the second barrier deformation is preserved. The likelihood of K-mixing as one passes over the inner barrier may be increased in view of recent theoretical findings that the inner barrier is unstable to deformations destroying the axial symmetry. In such a situation K is no longer a good quantum number. The outer barrier however is stable with respect to the degree of freedom destroying axial symmetry and hence a K distribution characteristic of the outer barrier deformation can be established and preserved.

We have also investigated the dependence of the nuclear level density on deformation and excitation energy to see at what excitation energy the shell effects are sufficiently dissolved so that the nucleus only "feels" the average properties approximated by a liquid drop model. Within the context of the model
assumed, 50 to 60 MeV is required to sufficiently destroy the shell effects so that the minimum state density occurs at the liquid drop saddle deformation. There is some tentative evidence that the transition from the outer barrier to the liquid drop barrier in being determinative of fragment anisotropies has been observed.  

14. ATOMIC PHYSICS

14.1 Introduction

D. Burch

The investigation of the atomic physics of high-energy ion-atom collisions which was begun last year\(^1\) has continued. The emphasis has been on the detection of Auger electrons which, when combined with simultaneous x-ray detection, provides a measure of the mean fluorescence yield. The apparatus used for detection of the electrons and x-rays is described earlier in this Report.\(^2\) In recent measurements we have been able to observe Auger groups from solid targets which was not possible with our previous apparatus.\(^3\) There is, however, considerable evidence now, both theoretical and experimental, that Auger and x-ray emission from heavy-ion-solid collisions can be an unreliable means of studying the primary ion-atom collisions. This is especially true for slow collisions when \(Z_{\text{ion}} \approx Z_{\text{target}}\).

We have consequently restricted ourselves to gas targets and, furthermore, to very thin gas targets (~5 mTorr). This latter restriction is the result of another recent development in this field -- namely, that the incident charge state can have a large influence on the ionization cross sections in heavy-ion collisions.\(^4\) The thin targets provide single (atomic) collision conditions which preserve the incident charge-state information.

A progress report on the subject of "Inner-Shell Ionization by Heavy Ions in the MeV Energy Range" is in preparation and will be presented at the Eighth International Conference on the Physics of Electronic and Atomic Collisions, Belgrade, July 1973.

2. Section 4.6 of this Report.

14.2 Auger Spectra in Heavy-Ion Collisions

D. Burch, J. Harris, W.B. Ingalls, and J.S. Risley

The electron spectra of C, CH\(_4\), O\(_2\), N\(_2\), Al, Ne, Ar, and Kr have been measured at several energies using incident protons, alpha particles, oxygen ions, and chlorine ions. Examples of proton and oxygen-ion excitation are shown in Figs. 14.2-1-4. Spectra produced by 12-MeV alpha particles appear identical to those produced by protons. The spectra produced by chlorine ions are similar to those following oxygen bombardment but are broader and shifted more to lower energies.
Fig. 14.2-1. Kr L-MM Auger spectra produced by 5-MeV protons (solid line) and 30-MeV O^8+ (open circles). The group is not discernible from the background in 30-MeV O^5+ collisions due to the presence of the electron-loss peak.

Fig. 14.2-2. Ar K Auger spectra produced by 5-MeV protons (solid circles) and 30-MeV O^5+ (open circles). The difference in the fluorescence yield is approximately 30% in these two collisions.

Fig. 14.2-3. Ne K-LL Auger spectra. These spectra were analyzed in Ref. 1 of Sec. 14.3 of this Report.
In several cases, the presence of the electron-loss peak can inhibit or prevent a study of the Auger group. This problem can be avoided with the use of highly-stripped ions.

The spectra produced by protons seem to imply an energy resolution somewhat worse than our electron-gun measurement of 1.4%. The reasons for this are not yet understood.

The spectra resulting from heavy ion bombardment are broad groups shifted to lower energies and constitute many unresolved transitions from highly ionized atoms. Attempts to identify possible transitions within the groups have been made on the basis of Hartree-Fock-Slater energy calculations. This procedure is limited, however, because the single-vacancy group is, itself, broad, and the relative intensities are sensitive to the degree of multiple ionization. Theoretical transition rates in defect configurations are necessary to interpret these spectra.

1. Section 14.6 of this report.

14.3. The Effect of Multiple Ionization on the Fluorescence Yield of Ne

D. Burch, R. Heffner, W.B. Ingalls, and J.S. Risley

K x-ray and K-LL Auger yields were compared in 5-MeV proton and 30-MeV oxygen-ion collisions on Ne. The degree of multiple ionization in the oxygen collision (KLn, n ~ 5) could be estimated from the x-ray energy shift of +50 eV and the Auger shift of -80 eV. The result was

\[ \bar{\omega}(30\text{-MeV oxygen}) = 2.4 \pm 0.5 \times \bar{\omega}(5\text{-MeV proton}) . \]

The energy shifts and fluorescence yields agree well with the calculations of Bhalla and Hein.

14.4 The Fluorescence Yield of C in Low-Energy Proton Collisions

D. Burch, D. Schneider*, and N. Stolterfoht*

Carbon is unique as the lowest-Z atom whose K-shell ionization can be readily studied via x-ray or Auger-electron detection. C has, consequently, been studied in detail through proton collisions and is continually being investigated at energies up to and beyond tandem limits. Recently, Toburen and Larkins\(^1\) compared existing Auger and x-ray cross sections in the proton-energy range of 2 MeV down to 300 keV. They found that at lower energies the fluorescence yield implied by these cross sections decreased with decreasing proton energy. If the same comparison is made with more recent data extending to 50 keV, the decrease in the fluorescence yield is even more dramatic — nearly a factor of 2.

It is known that the degree of multiple ionization increases with decreasing proton energy below \(\approx 400\) keV — a result which is apparent from the Auger spectra. Theoretical predictions are, however, that the fluorescence yield should, if changed, increase slightly in the presence of an additional L vacancy. The proposed\(^1\) explanation of this effect was that the x-rays emitted from the multiply-ionized atoms were shifted in energy above the C K edge and were consequently totally absorbed in the plastic x-ray detector entrance foil. The x-ray cross sections would then be too low by an amount precisely equal to the degree of multiple ionization, and, therefore, the fluorescence yield would artificially appear to decrease.

We have remeasured, simultaneously, the x-ray and Auger cross sections in P + CH\(_4\) collisions in the energy range of 50 to 500 keV. The x-ray detector efficiency was also measured at each proton energy. The NPL x-ray detector and "foil attachment" were mounted on the electron-spectrometer chamber\(^2\) at the Hahn-Meitner-Institut's AN-400 Van de Graaff accelerator. The proton beam intensity was typically 10 \(\mu\)A.

The foil transmission did not change with increasing multiple ionization. Therefore, the energy of a Carbon K x-ray from Methane with an additional L vacancy is not shifted above the K edge of C (in the form of Mylar). The fluorescence yield was also found to be constant in this energy range to within \(\pm 5\%\). This result shows clearly that relative fluorescence yields can be more accurately determined in simultaneous x-ray and Auger measurements. This is particularly true when the cross sections are very steep functions of the incident energy, as in the case of C. For example, for 75-keV p incident on C, a 1\% error in the absolute proton energy can give rise to a 10\% error in the fluorescence yield.

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14.5 K-Shell Ionization in $\text{Ne}^+ + \text{Ne}$ Collisions

D. Burch, D. Schneider, and N. Stolterfoht

Inner-shell ionization in slow ion-atom collisions is dominated by a mechanism which results from the formation of a transient quasi-molecule during the collision. In this process, a vacancy in an outer shell (of the incident ion, for example) can be transferred to an inner shell (of the target or projectile) providing the molecular orbitals generated by these two atomic levels are degenerate at some internuclear distance. The best understood example of this process is the transfer of a 2p vacancy to a 1s shell in symmetric or near-symmetric collisions. $\text{Ne}^+ + \text{Ne}$ is the simplest collision of this type. The AN-400 Van de Graaff accelerator of the Hahn-Weintner-Institut has been used to measure Auger-electron production cross sections at several angles in $\text{Ne}^+ + \text{Ne}$ collisions in the energy range of 50 to 600 keV. These results were combined with simultaneous measurements of the relative x-ray cross sections to determine the collision-energy dependence of the mean K-shell fluorescence yields. Auger electrons emitted from the target and projectile could easily be separated due to the "Doppler" shift of the projectile electrons. The degree of multiple ionization created in the collisions could be determined from the centroid energy shift of the Auger group (see Fig. 14.5-1). The electron spectrometer used for these measurements has been described in detail elsewhere.

Several aspects of this collision have been studied which can be briefly summarized as follows:

(1) Although there is a small systematic divergence of the two measurements, our absolute cross sections do not significantly disagree with the earlier results of Cacak, Kessel, and Rudd (50 to 300 keV).

(2) The degree of multiple ionization created is nearly independent of collision energy and is quite similar to that observed in 30-MeV $\text{O}^{5+} + \text{Ne}$.

(3) The fluorescence yield increases from a value of 1.2 to 2.0 times the "atomic value" in the energy range of 75 to 575 keV. The atomic value was
determined from 300 keV p + Ne using identical geometry. It is very surprising that the fluorescence yield can change by a factor of 2 and the degree of multiple ionization remain constant. At present, it seems that this can only be accounted for on the basis of a very specialized energy-dependent excitation of the remaining L-shell electrons. This result emphasizes the need for theoretical work in the field of transition probabilities in highly ionized and excited atoms.

(4) The energy and angular dependence of the electron "Doppler" effect have been studied and found to agree with simple velocity-triangle predictions (see Table 14.5-1).

<table>
<thead>
<tr>
<th>Ne⁺ Energy (keV)</th>
<th>Intensity Ratio</th>
<th>RMS Peak Position</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I(30°)/I(150°)</td>
<td>30° (eV)</td>
<td>150° (eV)</td>
</tr>
<tr>
<td>400 (T)</td>
<td>1.02 (1)</td>
<td>756</td>
<td>752</td>
</tr>
<tr>
<td></td>
<td>1.34 (1.36)</td>
<td>+166(151)</td>
<td>-150(151)</td>
</tr>
<tr>
<td>200 (T)</td>
<td>1.06 (1)</td>
<td>762</td>
<td>748</td>
</tr>
<tr>
<td></td>
<td>1.24 (1.25)</td>
<td>+113(113)</td>
<td>-108(108)</td>
</tr>
<tr>
<td>100 (T)</td>
<td>0.98 (1)</td>
<td>772</td>
<td>747</td>
</tr>
<tr>
<td></td>
<td>1.19 (1.17)</td>
<td>+72 (79)</td>
<td>-71(77)</td>
</tr>
</tbody>
</table>

Table 14.5-1. Typical data for Ne-Auger peaks of the target (T) and the projectile (P). Values in parenthesis are calculated.

(5) When kinematic effects on the solid angle are taken into account, we find that the Auger intensity from the target and projectile are nearly identical (see Table 14.5-1).

(6) After Doppler shift corrections, it was found that the Auger groups had different energies and widths at forward and backward angles. The difference increased with decreasing collision energy. Partial results are summarized in Table 14.5-1. This unexpected effect is probably the result of a distortion of the electron trajectories due to the near presence of the highly-charged collision partners.

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4. Section 14.3 of this Report.
14.6 Electron Loss in High-Energy Oxygen-Ion Collisions

D. Burch, W.B. Ingalls, and H. Wieman

Relative double-differential cross sections for electron production at 90° have been measured in the electron-energy range of 200 to 2500 eV in 17- to 41-MeV oxygen-ion single collisions with several gases using incident charge states of 3+ to 8+. A broad peak is observed at an electron energy slightly less than that corresponding to the incident-ion velocity (see Fig. 14.6-1). The energy and shape of the peak was found to be independent of target gas, and for a given target gas the peak intensity increased with increasing L-shell occupation of the incident ion as shown in Fig. 14.6-2. On the basis of the incident energy and charge-state dependence, the broad peak is attributed to electrons lost from the L shell of the incident ion.

A simple free-collision model of the electron-loss process based on electron elastic scattering from a screened Coulomb potential has been compared to the experimental data. Electron-loss cross sections are obtained by integrating the elastic-scattering cross section over the velocity distribution of the outermost shell of the ion. Numerical results using a 2s hydrogenic speed distribution for O^{4+} + Ar at 90° and several O^{4+} energies are shown in Fig. 14.6-3. The experimental data are also shown, normalized to the peak heights in each

![Fig. 14.6-1. Relative electron yields in O^{4+} single collisions with Ar. The yields are shown normalized to the number of 310-eV electrons.](image)

![Fig. 14.6-2. Relative electron yields in 30-MeV oxygen-ion single collisions with Ar for various charge states. Yields are shown normalized to the number of 310-eV electrons.](image)
spectrum. This model does account for the shape of the peak and for the shift below the incident-ion velocity (indicated by arrows in Fig. 14.6-3). The present relative measurements and background subtraction procedure do not yield information about the low-energy tail predicted by the model. For a given speed distribution, the magnitude of the tail depends only on the effective screening radius of the target atom. This radius has little effect, however, on the shape of the peak.

The shape of the theoretical peak is sensitive to the velocity distribution as shown in the 30-MeV spectrum of Fig. 14.6-3. Here the broader is distribution has also been used while keeping the ionization potential fixed at the O$^{1+}$ value of 113.9 eV. It is feasible that such measurements of this type could be developed into a means of determining momentum distributions for specific electron shells.

The prominence of the electron-loss peak is unique to the fast heavy-ion collisions which can be studied at Van de Graaff facilities where wide ranges of heavy ions, energies, and charge states are available. Studies of the electron-loss process via electron spectroscopy should provide very sensitive tests of electron-loss theories.

Fig. 14.6-3. Theoretical double-differential electron-loss cross sections at 90° compared to the experimental data normalized at the peak maximum in each spectrum. Details of the figure are discussed in the text.

14.7 Outer-Shell Excitation of the Rare Gases by 30-MeV Oxygen Ions

W.S. Bickel, D. Burch, J. Harris, W.B. Ingalls, J.S. Risley, and H. Wieman

It is well established that heavy-ion collisions result in high degrees of multiple inner-shell ionization. The motivation of the present work was an attempt to determine whether or not the additional electrons removed from the inner shells are totally ionized or are in part excited to high-lying levels in
the target ion. This type of information cannot be determined from Auger or x-ray spectra as they are typically insensitive to outer-shell excitation. The method of the experiment was a search for coincidences between outer-shell optical transitions and inner-shell Auger transitions.

Spectra in the visible region (2000–5500 Å) were measured with a 0.25 m Ebert monochromator (Jarrell-Ash, f/4.0, 600 grooves/mm, EMI 6256S and EMR 541 F photomultipliers) in 30-MeV oxygen-ion collisions with He, Ne, Ar, and Kr. Target pressures were 20 mTorr which resulted in oxygen beam charge-state equilibrium for each gas. The spectrometer entrance slits were 0.5 mm resulting in a resolution of 20 Å FWHM. The spectrometer viewed a corresponding path length of 0.5 mm with a solid angle of 3.5×10^{-2} sr. The lower wavelength limit was set by the absorption edge of the quartz exit window, the upper limit by the availability of photomultiplier tubes. The data were taken in a completely automatic mode using a digitized stepping motor for the grating rotation and were stored in a multiscaler which was externally advanced after a preset beam-current integration. The data were then dumped directly onto magnetic tape for analysis. Because of the high dark current in the phototubes it was necessary to employ a beam-dropout monitor which interrupted the data acquisition if the beam fell below a preset value. Typical spectra over a limited wavelength region are shown in Fig. 14.7-1.

In He 18 lines were observed all of which could be identified. In the other gases a total of over 100 lines were observed none of which have been positively identified thus far. It is quite possible that most of these lines have not been previously observed; an attempt to correlate these lines with previously published beam-foil results is in progress. We should emphasize, however, that the lines observed here are from the target atoms and not the incident ion. This is easily established from the absence of Doppler shifts and widths of the peaks. Of the gases studied, the light emitted from Ne was by far the strongest. Somewhat surprisingly, no light at all was observed in 5-MeV proton + Ne collisions.

A search for photon-electron coincidences was carried out for Ar L-MM, Kr L-MM, and Ne K-LL Auger electrons and photons in the wavelength region of 2000 to 3500 Å. The phototube was placed directly on the scattering chamber with a slit geometry such that the phototube and electron spectrometer viewed the same 2-cm path length. The electron resolution was degraded to 3% FWHM. Conventional fast timing using constant-fraction-discrimination and time-to-amplitude conversion was employed between the phototube and channeltron. True coincidences between photons and electrons were artificially established by chopping and bunching the oxygen beam to a FWHM of 0.5 nsec. This technique facilitated the electronics setup and provided an accurate estimate of the expected true-to-chance ratio. In the case of Ne a 100% coincidence between photons and electrons would have resulted in 24 true counts per hour. Half of this intensity could easily have been observed electronically but no true coincidences were detected. The same negative results were found for the other gases.

Although there certainly must be some optical transitions which result from "shake-up" following the inner-shell ionization and/or the Auger transition itself, we can definitely conclude that in the case of Ne these transitions do not lie in the 2000 to 3500 Å region.
Fig. 14.7-1. Rare gas spectra in the 2100 to 2900 Å region following 30-MeV oxygen-ion collisions. No strong lines in He were observed in this wavelength region. The data were taken on a scale of 1.87 Å/channel; the highest point in the Ne spectrum corresponds to 14000 counts. The ordinate represents observed counts not corrected for detection efficiency or solid angle. The dashed lines are the dark-current backgrounds.

The pulsed oxygen beam was also used to establish that the lifetimes of the 3 strongest lines in the Ne spectrum of Fig. 14.7-1 are shorter than 0.7 nsec. Further investigation of atomic lifetimes with the pulsed-beam technique are planned.

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15. MEDIUM ENERGY PHYSICS

15.1 Total Pion Nucleus Cross-Sections

M.D. Cooper, I. Halpern, and R.E. Marsh

This is a brief outline of the experiment which we are scheduled to do in the fall at the Los Alamos Meson Facility (LAMPF) in collaboration with Prof. Mark Jakobson (U. of Montana), Dr. D. Hagerman (Los Alamos), Dr. G. Burleson (New Mexico State University), Dr. J. Calarco (Stanford University) and their colleagues.

In our original proposal last year the scope and purpose of the experiment was described as follows. "We will measure total cross-sections for $\pi^+$ and $\pi^-$ mesons on a number of nuclei in the pion energy range from 50 to 300 MeV. The experiment will be performed on the LAMPF low energy pion channel. Results will be in the form of the total removal cross-sections which can be attributed to the target nuclei. These cross-sections will be interpreted in terms of the best available theoretical descriptions of the interactions of pions with nuclei. Among the questions of possible interest concerning these interactions are: The effect of the 3.3 pion-nucleon resonance on the pion-nucleus excitation function for different targets and incident energies, the differences in cross-sections for $\pi^+$ and $\pi^-$ mesons, and the differences in cross-sections for different isotopes of the same element. Which of these issues will receive the strongest emphasis will depend on our assessment of the level of interest and understanding of the problem together with the precision we find we can bring to each of the issues. The latter will depend, of course, on the magnitude of the background in these experiments. We are aiming for 2% absolute cross-sections and somewhat better relative cross-sections."

During the year we have been building and assembling the various pieces of apparatus that will be needed for the experiment. The interactions of incident pions passing through the target will be examined individually by a set of multi-wire counters (being made at Los Alamos) and by a stack of eight coaxial plastic scintillators subtending graded solid angle at the target. The five-foot diameter support ring for the scintillation counters was constructed in our shop and the counters are being assembled at Montana.

For an incident particle to be accepted as a pion of the correct momentum, it will have to properly trigger a DISC Cerenkov counter in its path (This counter is being built at Los Alamos). It will also have to trigger a separated pair of transmission scintillators to satisfy a time of flight and geometric criteria. Time of flight capability of the counters will be tested with an electronic circuit which simulates the R.F. structure of the beam and high counting rates encountered in the pion beam. This circuit is now under development in our electronics shop. Passage through the target is defined additionally by failure to trigger a halo counter in front of the target. These various counters and associated electronics are being developed here. The targets and target changing mechanism are also being built and assembled in our laboratory.

In addition to the work on equipment, some effort has been expended on
optical model calculations of pion-nucleus interactions. Such calculations prepare us for problems connected with the interpretation of our results.
16. RESEARCH PERFORMED BY USER OR VISITOR GROUPS

16.1. Total Body Calcium Studies in Humans Using Neutron Activation Analysis†


Studies have continued on the effects of various therapies in patients with bone wasting disease; 284 activations have now been performed in 120 patients. Thirty patients with osteoporosis treated with an androgenic agent for 2 years are completing their course of therapy; in this group regional bone mass was determined utilizing the technique of transmission densitometry (photon absorption). Correlation between regional bone mass and total body calcium (TBC) was quite good with an r value of .97.

A new investigation into the effects of 1-25 dihydroxycholecalciferol in renal osteodystrophy has begun; 20 patients with bone wasting secondary to chronic renal failure will eventually be studied with yearly neutron activation analysis (NAA).

Future plans include continued gathering of TBC data in normal individuals, and investigations into the effects of estrogens and fluoride upon osteoporosis.

In addition to the ongoing activation program, work has been done in support of a new technique to determine whole body calcium. The existing technique, based on detection of the gamma ray from the $^{48}\text{Ca}(n,\gamma)^{49}\text{Ca}$ reaction, requires a neutron dose of 200 mrad and the use of an expensive whole body counter. The new technique, using the $^{40}\text{Ca}(n,\alpha)^{37}\text{Ar}$ reaction, should require a maximum neutron dose of only 20 mrad and permits use of a proportional detector.

Since the argon is released in the lungs, body calcium can be determined by collecting the exhaled air, separating the argon from the other gases, and counting the $^{37}\text{Ar}$ inside a proportional detector. Although the technique is being designed for the use with a 14 MeV neutron generator, initial studies are being made with patients who are being irradiated by the University of Washington cyclotron as part of the ongoing NAA program. These studies are being carried out to determine the rate of excretion (biological half-life) in humans.

† Work supported in part by U.S. Atomic Energy Commission.
* Division of Nuclear Medicine, University of Washington.
1. The work on the new technique is supported by the National Aeronautics and Space Administration.

16.2 Fluorine 18 Production

G.M. Hinn*, W.B. Nelp*, and W.G. Weitkamp

The use of cyclotron-produced fluorine 18 as a bone cancer detecting agent has been a successful program over the past year. Demand for the isotope increased to the point that two two-hour runs a week were necessary to produce the
required amount. Over 1500 patients in the Seattle area received $^{18}_{\text{F}}$ produced at the University of Washington cyclotron.

Recently, however, the demand for $^{18}_{\text{F}}$ has fallen off abruptly as a result of the introduction of a new radiopharmaceutical, technetium 99m polyphosphate. This material enables bone metastases to be detected at an earlier stage, and is more economical to produce and distribute. Although production of $^{18}_{\text{F}}$ has been stopped, the technique and apparatus remain available if other uses should develop.

* Division of Nuclear Medicine, University of Washington.*

16.3 Fast Neutron Beam Radiotherapy

H. Bichsel*, J. Eenmaa*, K. Weaver*, D. Williams*, P. Wootton*, and W. Wycoff*

The overall objective of the project is to provide a measured, monitored, collimated beam of fast neutrons to permit development of a meaningful clinical trial comparing neutrons and photons as cancer treatment modalities. Initial studies are related to neutrons generated by cyclotron-produced 21-MeV deuterons incident on beryllium. The planned major modification of the cyclotron external beam system, described in last year's Annual Report, was postponed. This decision was based mainly on the need to achieve a beam suitable for the irradiation of patients as quickly as possible. The existing charged-particle beam line was modified only slightly and now does give us a suitable charged-particle beam for neutron production. The modifications consist of an extended yoke on the focusing magnet to allow increased magnetic field strengths, and an interchangeable shim arrangement which optimizes beam transmission and beam spot size and permits interchangeable operation with the physics beam line. The usable beam is about 30 percent of the cyclotron extracted beam and will be only about one half of the beam we were expecting originally, but still provides us with a dose rate of about 40 rads/min at the planned patient position. Activities and studies which have been in progress are summarized:

a) Target: The target is a 1.5 mm thick x 50 mm diameter beryllium disc. It is cooled by a thin layer of water 1/16 inch thick, flow rate 6 gal/min, in direct contact with the back surface of the beryllium disc. After more than 100 hours of beam-on time there has been no target failure nor sign of degradation of the original disc, as evidenced by surface appearance or by weight. A solenoid valve and water flow switch have been installed in series with the target to provide safety interlocks with the cyclotron.

b) Neutron beam: The angular distribution of the available neutron beam was determined and the beam location mapped out in the treatment area.

c) Shielding materials: Shielding materials were tested for activation, transmission of total dose, and energy of transmitted neutrons. Materials tested included steel, borated and non-borated water-extended resin, and Benelex.
d) Primary barrier: From the data on intensity distribution of the beam and properties of shielding materials, a compound barrier was designed. It consists of a 1 meter × 1 meter × 0.30 meter steel slab centered on the beam axis, pierced by a square opening to receive the exchangeable collimator assembly and permit transmission of the useful neutron beam. This steel barrier is supplemented by a sandwich of multiple layers of water-extended borated resin and steel plate, of similar geometry and central aperture. The shield support is on a system of air pallets to permit the total removal of the barrier at any time, and to permit alignment of the central axis with the central axis of the neutron beam.

e) Biology collimator: Because of the desirability of initiating the long-term biological-effect studies as quickly as possible, an interim collimator was designed and fabricated specifically for these experiments. This collimator consisted of 30 cm of aluminum-bronze alloy followed by 18 cm of borated plastic. The collimator insert was cast and machined with an aperture of square transverse cross section which was tapered to define the required neutron field. The insert was installed in the square hole in the main steel barrier. The neutron beam was explored and characterized and made available for the biological studies. These studies are reported in Sec. 16.4 and Sec. 16.5 of this Report.

f) Dosimetry studies: Dosimetry studies were initiated using tissue-equivalent ionization chambers and Rossi-type proportional counters (Shonka plastic, manufactured by EG&G, Santa Barbara). The approach to the ionization chamber dosimetry is based on calibration in a known $^{60}$Co gamma ray beam. A suitable $^{60}$Co gamma ray beam is available to us that has been calibrated with reference to standards directly traceable to the Bureau of Standards, EG&G at Santa Barbara, and the Clinical Physics Center, M.D. Anderson Hospital, Houston, Texas.

For our neutron beam, good agreement has been achieved for the total dose (i.e., rads/Coulomb), as measured by the ion chambers and the proportional counter. The proportional counter event spectra have been used to make preliminary estimates of the photon component of total dose "in air", and at the surface of, and within, a tissue-equivalent medium. The total dose as a function of depth in the medium has been determined. Studies are under way to establish more accurate values of stopping power and W values (i.e., average energy per ion pair) for various gases used in the ion chambers.

g) Therapy collimator: A collimator system to be used for patient treatment has been designed and the first units have been fabricated for testing and evaluation. The collimators consist of exchangeable water-extended borated resin inserts within the main shield barrier assembly described above. They are stepped to prevent neutron streaming and are cylindrical to permit rotation of the desired neutron field. The aperture for transmitting the beam is pyramidal in longitudinal cross section and can be any desired shape in transverse section.

The type and level of background radiation in the treatment area, with the machine off and on, has been mapped and studied extensively with the ionization chambers and scintillation counters. Preliminary cast concrete block barriers have been erected. The efficacy of the barriers and the final main barriers and exchangeable collimators is being evaluated.
16.4. Radiobiological Characterization of Radiotherapy Fast Neutron Beam

J.P. Geraci*, K.L. Jackson*, and G.M. Christensen*

The major objective of this program is to characterize biologically the neutron beam produced by the cyclotron by determining Relative Biological Effectiveness (RBE) and Oxygen Enhancement Ratio (OER) values for early and late damage to normal tissues of significance in cancer radiation therapy. The RBE and OER for acute injury in normal tissues also will be examined as a function of dose size and depth in a tissue equivalent medium.

During the past year, late effects studies of both the spinal cord and gastrointestinal tract were initiated. For the spinal cord investigation, the lumbar region of the spinal cords of mice was exposed to graded doses of X-rays or neutrons and the subsequent development of paralysis examined. To study late effects in the gastrointestinal tract, 4 cm segments of the small bowel were exposed to graded doses of X-rays or neutrons and the incidence of death due to intestinal obstruction noted. The preliminary neutron RBE value for late intestinal damage is 2.0 and 1.1 for spinal cord injury.

16.5 Radiation Oncology Using the Radiotherapy Fast Neutron Beam

J. Nelson*

Research in the Division of Radiation Oncology related to the Neutron Beam Therapy project concerns the response of normal mouse tissues and mouse tumors to fast neutrons. These experiments provide part of the biological characterization of the neutron beam from the cyclotron which precedes the treatment of cancer patients with neutrons.

The initial experiments were designed to determine the relative biological effectiveness (RBE) of the neutron beam compared to 250 kVp X-rays. To date, we have irradiated the skin of the feet of mice of the BALB/c strain with 1, 2 or 5 fractions of neutrons or X-rays. Fractions were given at 24-hour intervals. The tentative RBE's for early skin response (8-35 days postirradiation) are 1.79±0.05 for 1 fraction of radiation, 2.24±0.01 for 2 fractions, and 2.67±0.07 for 5 fractions. These same mice are being examined for late skin response and foot deformity.
Experiments are in progress to compare the effect of single and fractionated doses of neutrons and 250 kVp X-rays on the growth of a mouse mammary tumor. We are examining changes in the duration of the intermitotic cell cycle time and in the proportion of actively dividing cells, as opposed to reproductively resting cells, in this tumor, as a function of radiation dose and time after irradiation. We will relate these results to changes in growth potential of a tumor during a course of fractionated radiation therapy. The change in overall tumor growth rate as a function of radiation dose and fractionation scheme is also being determined by daily caliper measurements of subcutaneous tumors, allowing calculations of tumor volume.

† Supported by the National Cancer Institute, Grant No. CA 12441.
* Division of Radiation Oncology, Department of Radiology, University of Washington.

1 RBE is defined here as the dose of X-rays, in rads, needed to produce a specified degree of skin damage divided by the neutron dose in rads needed to reach the same endpoint.

10.6 Alpha Particle Injection into Reactor Materials


Alpha-particle irradiations of fast-reactor cladding and structural materials are being carried out under a program at Atomics International sponsored by the AEC-DRTT called "Irradiation Damage in Cladding and Core Structural Material", Task 2, Contract A.T.(04-2)-824 using the University of Washington's cyclotron. The cyclotron provides a fast and convenient method of introducing large concentrations of helium into various cladding candidates.

The program is divided into two sections. The first is the investigation of the variables, flux, fluence, temperature, and helium concentration, on the formation of voids in stainless steel. The cyclotron is used to implant helium in the alloys in a uniform manner at a low temperature. This is followed by accelerator proton irradiation to produce voids in the material. Electron microscopy is then used to ascertain the effects of the above mentioned variables on the size and distribution of the produced voids.

The second part is the study of high-temperature helium embrittlement in fast-breeder reactor cladding alloys. Helium is deposited uniformly in small sheet tensile samples prior to mechanical testing. Light and electron microscopy are used to study the effects of various thermo-mechanical treatments on the motion, agglomeration, and trapping of helium atoms and to determine the effect of helium on the mechanism of failure in the alloy.

* Atomics International, Canoga Park, California.

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16.7 Level Crossing in 44-min $^{199m}$Hg

B.D. Geelhood*, M.N. McDermott†, and R.J. Reimann*

The University of Washington cyclotron has been used to produce nuclear spin $I = 13/2$ 44-min $^{199m}$Hg for study by optical pumping and level-crossing techniques. The crossing of the hyperfine sublevels $|F, m_F\rangle = |15/2, 15/2\rangle$ and $|13/2, 11/2\rangle$ in the $^6P_1$ state has been observed and used to determine the value of the nuclear magnetic dipole interaction constant $A(^3P_1)$. A recent determination of the quadrupole interaction constant $B = -1010(18) \text{ MHz}$ by Kluge enables one to calculate an improved value $A(^3P_1) = -2298.38(18) \text{ MHz}$ and to predict the fields at which additional crossings should occur to within 13 signal linewidths. The observation of the weaker signals from one or more such crossings will fix the values of both $A(^3P_1)$ and $B(^3P_1)$ to high precision. Consequently, we are continuing attempts to make such an observation. An enriched $^{198}$Pt target has been obtained from Professor Sumner P. Davis, of the University of California, Berkeley, in order to increase the production of $^{199m}$Hg relative to other mercury isotopes.

† Work supported in part by the National Science Foundation.

∗ Department of Physics, University of Washington.


15.8 Particle Induced Fission

E. Neuzil∗

Use of the cyclotron by the Chemistry Department at Western Washington State College continues in the study of particle induced fission of elements and isotopes of the elements between Ta and Po on the periodic chart. The study includes the determination of the total fission cross section, charge distribution effects, angular momentum effects on the fission process, the shape of the fission fragment mass distribution curve and the excitation function for the fission process.

Several articles concerning the fission characteristics of medium-heavy elements at moderate excitation energies have been published, including one dealing with the dependence of fission on projectile particle angular momentum. The study of the fission properties of thallium isotopes is nearly complete and has been accomplished with the aid of the 88 inch cyclotron at the University of California at Berkeley as well as the 60 inch cyclotron at the University of Washington.

∗ Department of Chemistry, Western Washington State College, Bellingham, WA.
17. APPENDIX

17.1 Nuclear Physics Laboratory Personnel

Faculty

Eric G. Adelberger, Associate Professor
John S. Blair, Professor
David Bodansky, Professor
John C. Cramer, Associate Professor
George W. Farwell, Professor; Vice President for Research
I. Halpern, Professor
Fred H. Schmidt, Professor
Robert Vandenbosch, Professor
William G. Weitkamp, Research Associate Professor;
  Technical Director, Nuclear Physics Laboratory

Research Staff

David F. Burch, Research Associate
Martin D. Cooper, Research Associate
Ralph M. DeVries, Research Associate
Jørgen Pedersen, Research Associate
Ekkehard Prien, Research Associate
Willibrord M. Reisdorf, Research Associate
Geirr Sletten, Senior Research Associate
Kurt A. Snover, Senior Research Associate
James W. Tape, Research Associate
Michael S. Zisman, Research Associate

Laboratory Supervisory Personnel

Harold Faushka, Research Electronics Supervisor; Assistant
  Technical Director, Nuclear Physics Laboratory
John W. Orth, Accelerator Engineer; Assistant Technical
  Director, Nuclear Physics Laboratory

Predoctoral Research Associates

Chemistry

Phyllis A. Russo

Physics

Michael F. Baker
Douglas R. Brown
David Chamberlin
Robert H. Heffner
William A. Jacobs
David L. Johnson
Kwok-Leung Liu

Roscoe E. Marrs
K. Gopinathan Nair
Dennis L. Oberg
William Q. Summer
Herbert F. Swanson
William R. Wharton
Howard E. Wieman
Research Assistants

Chemistry

William B. Ingalls
Pui-Hing Lau
Douglas W. Potter
Michael Webb

Physics

John E. Bussoletti
Yuen-dat Chan
Bernardo Cuengco
Katsuyuki Ebisawa

Full-Time Technical Staff

Accelerator Operators

Barbara L. Lewellen

Accelerator Technicians

Carl E. Linder
Georgia J. Rohrbaugh
George E. Saling

Chemists

Joanne M. Heagney, Research Materials Scientist
Shirley Kellenbarger, Detector Maker

Design and Drafting

Peggy Douglass, Graphics Aide
David W. Gough, Designer
Lewis E. Page, Draftsman

Electronics Technicians

Laverne H. Dunning
Norman G. Ward

Engineering and Physics

Noel R. Cheney, Computer Systems Engineer
Rod E. Stowell, Electronics Engineer
Gary W. Roth, Physicist
Developmental Machinists

Norman E. Gilbertson
Charles E. Hart, Foreman
Gustav E. Johnson
Byron A. Scott, Student Shop Leadman
Anthony Virant, Leadman
Allen L. Willman

Administrative Staff

Susan E. Lambert
Karen M. Perry
Helene G. Turner, Administrative Secretary

Part Time Technical Staff

Ronald Aley
William Bertch
Marc Brittan
Jeffrey Dunham
Richard Funk
Lila Graham
David Hall
John Harris
Richard Methot, Jr.

Juan Ochoa
Brian Popp
Mojtaba Rezvani
Eric Schnellman
Thomas Stewart
Clarence Tennis
James Walker
Frederick Weiss

1. On leave from the Department of Physics.
2. Returned December 1972 to permanent position at Niels Bohr Institute, Copenhagen, Denmark.
4. At Centre Spectrometrie Nucleaire et Spectrometrie de Masse, Laboratoire Rene Bernas, Orsay, France, since September 1972.
5. Research Associate at Argonne National Laboratory since October 1972.
6. Terminated.

17.2 Advanced Degrees Granted, Academic Year 1972-1973

William R. Wharton: Ph.D. "A Comparison of the $^6$Li($^6$Li,$^6$Li*(3.56))$^6$Li* (3.56) and the $^6$Li($^6$Li,$^6$He)$^6$Be Reactions"
17.3 List of Publications

Laboratory Publications Which Appeared Since the 1972 Annual Report:


"Relativistic Kinematics for Two-Body Final States", W.J. Braithwaite, Computer Physics Communications 4, 227 (1972).


Laboratory Publications in Press or Submitted:


"Associated Legendre Polynomials, Ordinary and Modified Spherical Harmonics", W.J. Braithwaite (submitted to Computer Physics Communications).

"Relative Excitations of the $^{237}$Pu Shape Isomers", R. Vandenbosch, P.A. Russo, G. Sletten, and M. Mehta (submitted to Phys. Rev.).


"A Measurement and Microscopic Analysis of the $^{6}$Li($^{6}$Li,$^{6}$Li($^{3.56}$))$^{6}$Li($^{3.56}$) and the $^{6}$Li($^{6}$Li,$^{6}$He)$^{6}$Be Reactions", W.R. Wharton, J.G. Cramer, D.H. Wilkinson, J.R. Calarco, and K.G. Nair (to be published in Phys. Rev. Lett.).


Other Publications by Members of the Laboratory:


"(^{16}O,^{12}C) and (^{6}Li,d) as Alpha Transfer Reactions", R.M. DeVries, Phys. Rev. Lett. 30, 666 (1973).


"Preparation of Isotope Targets by Heavy Ion Sputtering", G. Sletten and P. Knudsen, Nucl. Inst. and Meth. 102, 459 (1972).


"Double Gamma Decay in ^{40}Ca", E. Beardsworth, R. Hensler, J.W. Tape, N. Benczer-Koller, W. Darcey, and J.R. MacDonald (submitted to Phys. Rev.).


Papers Given at Meetings and Conferences:


"A Comparison of the $^6$Li($^6$Li, $^6$Li$^*$(3.56))$^8$Li$^*$(3.56) and the $^6$Li($^6$Li, $^6$He) $^8$Be Reactions as a Study of Charge Dependence", W.R. Wharton, J.G. Cramer, and J.S. Blair, Bull. Am. Phys. Soc. 17, 920 (1972).


"Spectroscopy of $^{12}$C and $^{8}$Be as Observed in the $^{16}$O($a,2a$) and $^{12}$C($a,2a$) Reactions", J.D. Sherman, D.L. Hendrie, and M.S. Zisman, Bull. Am. Phys. Soc. 17, 930 (1972).


