ANNUAL REPORT

Nuclear Physics Laboratory
University of Washington
June, 1974
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

Although it was possible (and convenient) to arrange this year’s research contributions under a limited number of major headings in the table of contents, an examination of the actual titles listed there will show that the Laboratory activities and interests continue to range broadly over the fields of nuclear physics. The tradition of variety that has long existed here is in part a reflection of the teaching- and student-oriented character of the Laboratory. This tradition provides a natural mechanism for the shifts of major interests of the staff with time. Thus although there was considerable work, in former years, on excitations of low-lying levels by inelastic scatterings, on statistical emissions from nuclei and on nuclear fission (just to mention a few examples) there is relatively little concern with these subjects in the present report. Taking their place as subjects of major interest, at least for this year, are heavy ion interaction mechanisms, the possibility of characterizing high-lying nuclear excitations as collective multipole excitations, the structure of levels in light nuclei as revealed by their decay modes, and the nature of proton interactions with nuclei as revealed by the use of polarized proton beams. In addition, there are a number of areas of high interest that are neither growing nor shrinking, for example studies of nuclear astrophysics, of the parity-violating component of the nuclear forces, and of inner shell ionizations of atoms produced by fast projectiles.

Along with, and in support of, these shifts in physics interests, there have been significant developments of the technological resources of the Laboratory, e.g., the continued improvement of the polarized ion source and the installation of an ion source in the high voltage terminal of the injector stage of our three-stage FN tandem.

There may be some other transformations going on in the style of the Laboratory activities in addition to those associated with the evolution of our physics interests. We notice (see Appendix) that this year seven advanced degrees were granted on work done in the Laboratory. We recognize this as an upward fluctuation on what appears to be a steadily falling curve. This year we have had more visitors who have come to collaborate with us on experiments than we have had in the past, and we have, in turn, gone more frequently to other facilities to do experiments that we could not do at home. Included here is our program on pion-nucleus physics (A first run of LAMPP experiment #2 on total pion-nucleus cross-sections was scheduled for May), as well as a number of different studies at Berkeley accelerators. Finally, we should mention what seems to be an increasing interest in problems related to applications of nuclear physics. A group has been studying nuclear energy-related questions, and there has been a substantial increase in the level of medical researches which make use of the cyclotron.

We close the introduction with the standard reminder that the articles in this report describe work in progress and are not to be regarded as publications nor quoted without permission of the investigators. The names of the investigators on each article have been listed alphabetically but where appropriate, the name of the person primarily responsible for the report has been underlined.
As always, we welcome applications from outsiders for the use of our facilities. As handy reference for potential users we list in the table below the vital statistics of our accelerators.

THREE STAGE TANDEM VAN DE GRAAFF ACCELERATOR
(A High Voltage Engineering Corp. Model FN)

Completed: 1957
Funding: Purchased with NSF funds; maintained by AEC funds and some funds from the State of Washington.

Beams currently available:

<table>
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<tr>
<th>Ion</th>
<th>Typical Current (nA)</th>
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<tbody>
<tr>
<td>p, d(3 stage)</td>
<td>1000</td>
<td>25</td>
</tr>
<tr>
<td>p, d(2 stage)</td>
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<tr>
<td>polarized p</td>
<td>15</td>
<td>18</td>
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<tr>
<td>He</td>
<td>800</td>
<td>27</td>
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<tr>
<td>Li</td>
<td>500</td>
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</tr>
<tr>
<td>C</td>
<td>50</td>
<td>63</td>
</tr>
<tr>
<td>N</td>
<td>30</td>
<td>72</td>
</tr>
<tr>
<td>O</td>
<td>1000</td>
<td>81</td>
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<tr>
<td>Cl</td>
<td>1000</td>
<td>99</td>
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CYCLOTRON
(A 60-inch fixed energy machine)

Completed: 1952
Funding: Constructed primarily with State funds and subsequently supported by AEC funds. Now sustained by funds from outside users.

Beams currently available:

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<td>p</td>
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<td>d</td>
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<td>&quot;He&quot;</td>
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<td>3.2</td>
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1. ACCELERATOR DEVELOPMENT

1.1 Van de Graaff Accelerator Operations and Improvements

Staff

Three milestones were passed in Van de Graaff operations during the past
year: The first $^{170}$ beam was accelerated, the highest energy beam to date,
25 MeV, was produced, and the first beam emerged from the injector terminal ion
source. The injector was shut down for installation of the terminal ion source
in January, and first produced beam in April. Details of the terminal ion source
project are given in Secs. 1.2 and 2.1. Statistics of Van de Graaff operations
are given in Table 1.1-1.

The following are among the improvements made to the accelerator and its
peripheral equipment during the year.

a. A number of improvements were made to the 45 deg left beam line, on
which the 10" x 10" NaI crystal is located. A new beam aperture box was built,
consisting of 2 wheels separated by about 18 in. Each wheel has 5 ports and
each port will hold 2 apertures, permitting a variety of apertures to be selected
and positioned under vacuum by a simple rotation of the wheel. A rigid table
was built up from the basement floor to support the beam line and aperture box,
allowing elimination of some of the overhead supports, which were too flexible.
The vacuum system was completely rebuilt with a new diffusion pump, an in-line
liquid nitrogen cold trap, and a large roughing pump. The beam line now possesses
greatly improved mechanical rigidity as well as improved pumping speed and a
cleaner vacuum.

b. The compressor was replaced on the system which scavenges gaseous
nitrogen from the liquid nitrogen cold traps and reservoir. The new pump,
which is of a type that will not allow air to enter through the bearings, enables
us to collect 10,000 cu. ft. in 24 hours. An oxygen analyzer was installed in
the system to monitor for air leaks.

c. Increased rate of resistor failure in the tandem has led to the design
of a new type of column resistor. Prototypes were tested successfully for six
months in the tandem. Fabrication of a complete set of resistors is presently
under way.

d. A portable high vacuum system which can contain any of the ion sources
in the Laboratory has been built for testing and general use.
Table 1.1-1. Statistics of Van de Graaff Operation from April 16, 1973 to April 15, 1974

1. Division of time among activities

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<tr>
<th>Activity</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
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<tbody>
<tr>
<td>Normal operation a)</td>
<td>6680</td>
<td>75</td>
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<tr>
<td>Scheduled maintenance b)</td>
<td>867</td>
<td>10</td>
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<tr>
<td>Unscheduled maintenance</td>
<td>229</td>
<td>3</td>
</tr>
<tr>
<td>Unrequested time</td>
<td>984</td>
<td>11</td>
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<tr>
<td><strong>Total</strong> c)</td>
<td><strong>8760</strong></td>
<td><strong>100</strong></td>
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2. Division of beam-on time among particles

a. Two-stage operation

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<th>Particle</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
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</thead>
<tbody>
<tr>
<td>Polarized protons</td>
<td>1032</td>
<td>15</td>
</tr>
<tr>
<td>Protons</td>
<td>1251</td>
<td>20</td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td>697</td>
<td>11</td>
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<tr>
<td>$^4\text{He}$</td>
<td>463</td>
<td>7</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>306</td>
<td>5</td>
</tr>
<tr>
<td>$^{14}\text{N}$</td>
<td>171</td>
<td>3</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>674</td>
<td>11</td>
</tr>
<tr>
<td>$^{17}\text{O}$</td>
<td>26</td>
<td>&lt; 1</td>
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<td>$^{18}\text{O}$</td>
<td>292</td>
<td>5</td>
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<tr>
<td>$^{35}\text{Cl}$</td>
<td>410</td>
<td>7</td>
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<tr>
<td><strong>Total</strong></td>
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<td><strong>85</strong></td>
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b. Three-stage operation

<table>
<thead>
<tr>
<th>Particle</th>
<th>Time (hrs)</th>
<th>Per Cent</th>
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<td>Deuterons</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>968</strong></td>
<td><strong>15</strong></td>
</tr>
</tbody>
</table>

**TOTAL BEAM TIME** 6290  100

---

a) Includes all the time accelerator was under control of an experimenter.
b) Does not include time for installation of the terminal ion source in the injector.
c) This is the number of hours in one year.

1.2 Terminal Ion Source Support Structure

G. Roth and W.G. Weitkamp

Installation of the terminal ion source (TIS) described in Sec. 2.1 has changed the forces on the column and beam tube of the injector. It has been important to understand these changes and to design support structures correctly not only to minimize the risk of catastrophic failure such as occurred with the...
injected beam tube earlier, but also to prevent distortions in the beam tube and ion source that might reduce the output beam intensity.

The two changes in forces have been identified and studied: the change in weight carried by the terminal, and the change in axial force on the beam tube due to the pressure of the insulating tank gas on the source. The results of our studies are presented below in some detail because such structural analyses of Van de Graaff accelerators are not generally available.

Problems involved in adding weight to the terminal were recognized early in the design process, and an effort was made to minimize the total weight of the ion source, pump and electronics, and to maximize the weight of components removed from the terminal before TIS installation. As a result, the terminal actually carries slightly less weight than it did prior to TIS installation.

The axial force on the beam tube has been somewhat more difficult to deal with. A tandem accelerator normally does not have any such axial forces on the beam tube because the tube runs all the way through the pressure vessel. In our design, the TIS caps off the beam tube in the terminal, resulting in a force of about 8000 lbs at full tank pressure. In the prior configuration of the injector, there was a pumping tube running from terminal to tank base supporting an axial force, but this tube did not require accurate alignment, so that problems of supporting it were simpler than has been the case with the TIS.

Description of the columns. A cross section through a column of an HVE FN tandem is shown in Fig. 1.2-1. The principal structure components are four glass pads about 1 in. thick indicated by cross-hatching. These pads, glued together, form four horizontal pillars which bear the forces on the column. The beam tube is located on a side of the column as shown, but is structurally independent of the column. A schematic side view of the high energy and neutral columns, together with the forces on the columns is shown in Fig. 1.2-2. Horizontal lines represent the glass pillars. The neutral column is attached rigidly to the tank base at four points, each point in line with the center line of a glass pillar. The high energy column is attached by rollers which permit the column to move axially, but which apply the indicated vertical forces.

Since the column is not designed to support large stresses in tension, a compressional force of 56,000 lbs is applied to the high energy column by an adjustable spring. Under normal conditions, i.e., without the TIS installed,
the compression in each upper pillar increases from 9,500 lbs to 28,000 lbs as one moves from tank base to terminal. The compression in each lower pillar decreases from 18,500 lbs at the base to 200 lbs at the terminal. The compression in the lower pillar at the terminal is just that required to support the load in the terminal region.

Design and Testing of the TIS Support Structure. The support for the TIS must satisfy the following criteria: a) No component must be stressed beyond safe limits, either under static conditions or in the presence of vibration, when the accelerator is evacuated or pressurized. b) Neither the ion source nor beam tube must be distorted or displaced enough to affect beam output. And c) assembly, alignment, and maintenance must be as easy as possible.

Two tests of column properties were made to provide design data. The first measured the lateral stiffness of the column, and was basically a test of our ability to predict column properties with a simple model of column structure. The displacement of the terminal per unit force was measured in both the vertical and horizontal directions, and compared with a calculation assuming that each column is composed of four cantilevered glass pillars. A modulus of elasticity of $1 \times 10^7$ psi, a typical value for glass, was used. The results given in Table 1.2-1 show that measured displacements are larger than calculated. This

<table>
<thead>
<tr>
<th>Table 1.2-1. Terminal displacement in units of $10^{-4}$ in./lb</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>5.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Vertical</td>
<td>1.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

is because the column mounting fixtures at the tank walls are not rigid, so that the elasticity of these rather complicated fixtures must be considered in a correct calculation.
The easiest way to mount the TIS would be to bolt the source as rigidly as possible to the terminal end of the high energy column. This would result in a torque on the column when the accelerator is pressurized, since the center of pressure on the source is 13 in. from the center of the column. The second test studied the effect of applying this torque to the column. A calibrated hydraulic cylinder applied a known force through a cable to a bar bolted to the terminal weldment. Both the horizontal displacement of the terminal and the bending of the column were measured while applying a torque $1 \times 10^5$ in.-lb, equivalent to full tank pressure. The beam tube was not rigidly attached to the column during this test. The results are given in Table 1.2-2, together with results of a calculation similar to the one mentioned above. The agreement between measured and calculated quantities is satisfactory here considering the approximations in the calculations, and the uncertainty in the column radius measurement of about ±50%.

With this torque applied to the terminal, a net tension of about 2000 lbs appears in the lower pillar on the opposite side of the column from the beam tube at the point where the pillar connects to the terminal weldment. The tension disappears rapidly as one moves down the column toward the tank base because of the increasing compression mentioned above. This point at the terminal is thus the weakest point in the column. The column is designed to support such a tension; during assembly of the column, when column sections are supported entirely by the ends, a comparable tension appears in the lower pillars. However, this tensional stress is uncomfortably near the stress at which we believe the glass in the beam tube fractured previously.\(^1\)

For this reason, we designed the TIS support structure so that the axial force is carried almost entirely by the beam tube, and not by the column. The beam tube couplings are rigid pieces of pipe, capable of bearing the entire axial force. The coupling between the beam tube and the ion source is a bolt-reinforced bellows which can be assembled easily and permits independent alignment of the beam tube and source, but which, when tightened, can withstand the axial force with negligible distortion. The mounting brackets in the terminal for the source and ion pump hold the source rigid laterally, but permit flexing axially so that the axial force is transmitted to the beam tube.

The TIS has now been pressurized several times without indications of any difficulty. However, further testing is planned to insure the safety of the design.
2. A turn counter measured the tension in this spring. The calibration of the counter is 415 lb/turn.

1.3 Beam Jitter Suppressor

H. Fauska and W.G. Weitkamp

Electrostatic coupling between the charging belt and the beam tube in a Van de Graaff accelerator causes the emerging beam to "jitter" slightly in position. In an accelerator equipped with inclined field tubes this jitter can be several mm in magnitude in the vertical plane. In the horizontal plane the jitter is usually much smaller, but it can cause a high frequency terminal voltage regulator, such as the one described in Ref. 1, to introduce an energy spread in the beam.

A device to correct for beam jitter has been described previously, but this device was AC coupled, making it difficult to adjust, and was only capable

Fig. 1.3-1. Block diagram of the beam jitter suppressor.
of suppressing jitter in the vertical plane. A DC coupled system which also includes horizontal jitter suppression has now been installed on the accelerator.

Since the horizontal and vertical modes of suppression use identical electronics, only one mode is shown in the block diagram of Fig. 1.3-1. The beam current intercepted by a slit jaw forms the signal fed into the first stage of amplification. This stage amplifies the logarithm of the signal, so as to minimize gain changes when the beam intensity changes. Signals from slit jaws left and right of the beam (or above and below) are fed into a difference amplifier. The output drives two high voltage tubes, which in turn drive electrostatic steering plates.

When properly adjusted, the circuit holds the beam precisely centered between the slit jaws. The system typically reduces jitter by about a factor of 10. One can use either the object slits upstream or the image slits downstream of the 90° analyzing magnet as the source of the correcting signal. Normally, the object slits are used, but it is sometimes desirable to use the image slits to suppress jitter in a specific heavy ion beam in the presence of other beams.

1. C. Roth and W.G. Weitkamp, Nucl. Instr. and Meth. to be published.

1.4 Control of the Beam Position on Target Using the Switching Magnet

J.G. Cramer and H. Fauska

A controller to correct for horizontal movement of the ion beam on target was designed and built.

The input signal to the controller comes from a split Faraday cup, and may be either an electrometer signal or a pulse train from a Dymec current-to-frequency converter.

A block diagram of the unit is shown in Fig. 1.4-1. The inputs are fed into a difference amplifier through a dual potentiometer thus providing balancing or adjustment of the beam on the split cup. The difference amplifier provides front panel adjustment, and drives the power amplifier which energizes the degaussing coils of the switching magnet. Gain selection is provided on the power amplifier.

Initial tests with the system while viewing a TV target showed a marked improvement of the stability of the beam position on target.
Fig. 1.4-1. Block diagram. Controller for beam position on target.

1.5 Updating the Solid State Klystron Bunching System

H. Fauska and N.G. Ward

The original solid state buncher system for the Van de Graaff accelerator has been in use for many years, and was in need of modification to reduce experimental setup time, improve reliability, modernize circuitry, and provide extra outputs at various points in the system.

The updated system uses TTL integrated circuits where possible. A front panel switch allows the chopper pulse frequency to be divided by factors of 1, 2, 4, or 8. Relative to the buncher RF frequency several extra outputs are provided with NIM fast pulse logic levels. A stable step attenuator has been added to the buncher RF driver line, and provides a precision control of the RF amplitudes on the buncher. Control room adjustment of the chopper plate potential has been included to allow correction for any beam steering. In addition, the buncher tube supports were shimmed to improve alignment. Initial tests showed that the updated system was working satisfactorily.

1.6 Cyclotron Operations and Improvements

Staff

The cyclotron continues to be used primarily for medical and nuclear reactor research. Statistics for cyclotron operations during the year are given in Table 1.6-1. Brief reports of research conducted at the cyclotron by outside users groups are given in Sec. 17 of this report.

Extensive alterations have been made in the cyclotron building to accommodate this research. A patient waiting room and two medical laboratory areas have been constructed, and a partition has been erected to separate normal laboratory functions from medical activities as much as possible. Instrumentation control rooms have been provided for both the cancer therapy and nuclear engineering groups.

Considerable effort has been spent in improving safety conditions at the cyclotron, both to comply with new standards, as well as to provide for the requirements of the medical activities. Automatic emergency lights and an emergency hand operated mechanism for opening the main shielding door have been installed. The interlock system has been revised to facilitate patient treatment in the cyclotron vault. An extensive study of the automatic fire extinguisher system on the cyclotron has been made to assure that there is minimal hazard to patients from CO₂ inhalation in the event the system is tripped during a treatment period.
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<th>1. Division of time among activities</th>
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<th>Per Cent</th>
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<td>4</td>
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<tr>
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<td>Deuterons</td>
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<tr>
<td>Total</td>
<td>868</td>
<td>100</td>
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</table>

<table>
<thead>
<tr>
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<th>Per Cent</th>
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<tr>
<td>University of Washington Department of Radiology</td>
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<tr>
<td>FAST Neutron Cancer Therapy</td>
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<td>In Vivo Fast Neutron Activation Analysis</td>
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<td>of Calcium</td>
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<td>University of Washington Nuclear Physics Laboratory</td>
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<td>11</td>
</tr>
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<td>University of Washington Department of Physics</td>
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<td>5</td>
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<tr>
<td>University of Washington Department of Nuclear Engineering</td>
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<td>3</td>
</tr>
<tr>
<td>Atomics International</td>
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</tr>
<tr>
<td>Western Washington State College</td>
<td>9</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Total</td>
<td>1741</td>
<td>100</td>
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</table>
2. ION SOURCE DEVELOPMENT

2.1 Terminal Ion Source

G. Roth and Staff

The construction and installation of a terminal ion source for the injector stage of the three-stage Van de Graaff accelerator has been completed. At this writing the machine has been operated for one preliminary test with the terminal charged to 3.5 MV and in which beam was detected at the exit of the injector.

The terminal ion source is expected to increase the versatility of the injector in several ways. a) First, a great variety of ions can now be obtained from the injector whereas previously only $^3$He and $^4$He were available. All ions commonly produced from a direct extraction duoplasmatron have been obtained from the source on the test stand. b) It is expected that it will be possible to run the terminal at higher potential than heretofore (about 8 MV rather than 6.5 MV) because of the removal of the low energy beam and pumping tubes. This eliminates effects of the intense neutral beam and of the deterioration of these tubes. c) Operation of the injector for heavy ions will mean that these ions reach the tandem stripper with an energy of 17 MeV and higher charge state stripping will take place than in two-stage operation where the stripping energy is only 9 MeV. d) Finally, the $^3$He and $^4$He beams will be a factor of ten larger than the usual 0.3 and 0.5 u.a.

The various components for the source had all been tested earlier. The various systems were assembled together on a wooden mock-up of the terminal and tested extensively. Air cooling of the duoplasmatron has proved to be very effective, resulting in a saving in cost, design effort, and complexity. The permanent magnet used for the plasma constrictions has shown itself to be satisfactory. Source and power supply stability have been extensively monitored with good results. Pressure testing was carried out in a test vessel on the ion pump case, the duoplasmatron and the power supply assembly, all with no ill effects.

Installation of the source into the injector terminal was begun in January 1974. Two important questions needed answers before the injector was committed to complete installation. Could the column structure support the forces introduced by installing the source and were the electronics power supplies capable of withstanding tank sparks reliably? Thus partial disassembly of the injector which avoided removal of beam tubes and other critical components of the neutral-negative source was done to answer these questions. The column structure was studied extensively and the results are discussed elsewhere in this report. No ill effects were observed. It was of course not possible to determine by bench tests whether the source power supplies would be reliable during accelerator tank sparking. Therefore just the power supply rack was mounted in terminal, attached to dummy loads and the accelerator was closed. A rod was inserted through the tank wall to cause the terminal to spark at a potential of 6 MV. Over 500 sparks during a several hour period caused no component failure.
Fig. 2.1-1. Left side of injector terminal showing source and pump.

Having answered these two questions, all unnecessary equipment was removed from the injector and the terminal ion source was installed. Figure 2.1-1 shows the left side of the injector terminal. The duoplasmatron is in the center and the readout lenses are in the cylinders seen above and below the duoplasmatron. The source attaches to a pumping tee containing the bending magnet. The ion pump case can be seen in the center of the terminal structure. Figure 2.1-2 shows the ion source separately. The top structure is the duoplasmatron with the permanent bottle magnet housed in the dark colored cover. Beam is extracted at 25 KV and focused by an Einzel lens.

Figure 2.1-3 shows the right side of the terminal with the power supply rack occupying most of the space. The upper supplies float electrically at the 25 KV extraction potential and the lower supplies are at terminal ground potential. To the right of the supplies are the control rods and linkages and to the left are the gas valves, also floating at extraction potential.

The installation has been completed and the final step of the project will be to operate the accelerator in a three-stage configuration while checking the performance of various ion beams.
Fig. 2.1-3. Right side of injector terminal showing power supplies.

2. See Sec. 1.2 of this report.

2.2 Polarized Ion Source

E.G. Adelberger, H.F. Swanson, and T.A. Trainer

Polarized ion source development has been concentrated in three major areas during the past year. The reliability of source components, particularly the duoplasmatron and cesium cell, has been considerably improved. A careful examination of the fast spin-flip system developed for the parity-violation experiment has resulted in a significant reduction of spin-correlated beam steering. And a program has been undertaken to make major modifications to several source components.
Fig. 2.2-1. Polarized Ion Source

The present ion source configuration is shown in Fig. 2.2-1. Stability of the positive ion source and cesium charge-exchange cell has been a chronic problem in the past. Installation of a molybdenum insert in the probe electrode for the duoplasmatron and an all-copper anode have eliminated problems associated with melting of these elements. No deterioration has been observed in five months of operation. Severe sputtering of the aperture in the accel electrode has been reduced by including a molybdenum insert. This insert must be replaced after one month of operation, but there is no longer need to replace the entire electrode. A system of dowel pins has been installed in order to insure accurate and reproducible alignment of the accel electrode. This system is a temporary measure until equipment is installed for remote positioning of the accel electrode. A 70° conical expansion cup and decel electrode have been installed. These modifications have resulted in a 70% increase in extracted beam. The duoplasmatron produces 10-12 mA of positive beam for a period of 10-15 days, after which filament replacement is required.

A new cesium canal has been installed. The canal is a copper tube 1.25 cm diameter by 15 cm long. The previous canal included a large diameter chamber in the center which, after a short period of operation, made the response time of the cell for cesium density adjustment too long. The response time for the cesium metering valve is now a few seconds. Further changes are planned to reduce the heat capacity of the cesium cell so that the cell is equally responsive to changes in heater current. This will allow efficient adjustment of cesium density while the source is at high voltage.

With the improvements noted above and the modified Einzel lens described below the polarized source routinely provides target proton beam currents of 10-15 nA with a beam polarization of 0.70-0.75. The source has operated without maintenance for up to 13 days.

Construction of a device to allow remote positioning of the accel electrode is about half completed. This device allows transverse and longitudinal adjustment of the accel electrode with respect to the beam axis while the source is at high voltage. Sensitivity is expected to be equivalent to a discrete motion of 0.025 mm. The device should insure consistent operation of the positive ion source independent of mechanical alignment of electrodes.
While polarized source stability is presently satisfactory, beam intensity and polarization are considerably lower than should be expected. Diagnostics and ion-optic calculations have revealed several areas where redesign would be profitable. Some of these problems are considered below.

In order to provide improved pumping and transverse field cancellation in the crossover region an additional vacuum enclosure will be installed with a third diffusion pump. This enclosure will allow installation of a gate valve to isolate the duoplasmatron for quick servicing and a beam scanner and variable crossover aperture for diagnostic work. The enclosure will also serve as a superstructure for supporting three pairs of Helmholtz coils used to provide optimum crossover fields.

The proximity of the first Einzel lens to the argon cell and poor pumping in this region lead to considerable charge exchange inside this lens in addition to that in the argon cell. This effect combined with a small lens diameter lead to a marked degradation of the beam emittance and polarization. This lens has been enlarged as much as the present vacuum enclosure allows (from 3.8 cm to 5.7 cm diameter) with a 50% increase in polarized beam. However, a further size increase and better pumping require an enlargement of the present vacuum enclosure.

The present system for orienting the spin involves a Wien filter and spin-rotation solenoid. Because of space limitations this system requires two closely spaced beam crossovers. These crossovers contribute to beam emittance and place severe restrictions on the admittance of the spin-rotation devices which are not satisfied in the present design. It is planned to combine both functions in a rotating Wien filter which will require only one crossover and occupy half the space. An additional advantage of such a filter is that accurate spin orientation will no longer depend on a current measurement.

Ion optic calculations indicate that the present acceleration tube is unsatisfactory. A design effort is in progress to develop an acceleration tube meeting several criteria. The tube should be easily disassembled and self aligning. It should have good pumping characteristics and voltage-holding capability. The optical properties should be consistent with a magnification considerably less than unity and an acceptance well matched to the entering beam phase space. In addition the optical properties should not be sensitive to the overall accelerator voltage.

1. See Secs. 7.2 and 9.1 of this report.

2.3 Development of a Sputtering-Type Ion Source

J.G. Cramer, C.E. Linder, K-L Liu, and M.S. Zisman

A sputtering ion source similar to that described by Middleton and Adams\(^1,2\) has been constructed and is undergoing tests. It differs from the Middleton source in two important aspects: (a) It has a focusing element between the
source of Cs ions and the sputtering target, and (b) it uses a wick3 constructed of Ni wires which conducts molten Cs metal to the vaporizing heater, thereby improving the time response of Cs flow to changes in vaporizer temperature.

The source has produced over 1 μA of C beam, but is not yet considered operational because of stability problems due to thermal coupling between the vaporizer and ionizer heaters. This coupling has been removed by replacing the short length of Mo tubing between these two units by a loop of stainless steel tubing, but this modification has not yet been tested.

The value of the focusing element mentioned above has been demonstrated in testing by the pronounced effect this element has on beam intensity. The beam intensity is diminished by a factor of 2 to 5 by slight changes in focusing potential. It seems unlikely that a source without this element would have sufficiently accurate focal properties to give comparable performance. The lens potential also acts as a barrier to prevent low energy electrons4 from traveling backward through the source from the sputtering region to bombard the ionizer plug.

Work is continuing on the source. It is hoped that experience with the prototype source will lead eventually to the design of a source suitable for operation in the terminal of the injector tandem.

4. R. Heider, Oxford University (private communication).

2.4 Modification of Ion Source Technique for Cl− Beams

D. Burch

The method of producing Cl− beams with the Direct Extraction Ion Source (DEIS) has been improved over the "vapor pressure" method reported earlier.1 An otherwise evacuated bottle containing CCl4 is now inserted on the source side of the H2 leak. The amount of CCl4 vapor added to the H2 is controlled by a Granville-Phillips precision leak. With the CCl4 valve closed a residual 35Cl− beam of 0.5 to 1.0 μA is typically present; this beam is increased by a factor of 10 or more by opening the CCl4 leak to a reproducible setting without significantly increasing the source pressure. This technique requires a sensitive needle valve. Stable operation of the source over three-day runs at 8 μA of Cl− is typical.

3. INSTRUMENTATION, DETECTORS, RESEARCH TECHNIQUES

3.1 Design and Construction of Electronic Equipment

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

Major electronic projects are discussed in Secs. 1.3, 1.4, 1.5, and 3.2 of this report. Additional projects completed during the last year include the following:

A. A new corona regulation system using a 6BK4 tube and a suitable solid state difference amplifier was constructed to replace the original 4-125A tube and the associated difference amplifier. The new system has performed satisfactorily for the past seven months.

B. Several constant fraction discriminators were constructed along the design of the Technical University of Munich.

C. To solve the great demand for preamplifiers encountered when using Multi-detector arrays in the scattering chamber and to reduce set-up time, an eight channel pre-amp unit was constructed. Connections to bias supplies and detectors are implemented with multi-wire connectors instead of individual BNC's.

D. A digital counting rate sensor with a control output was designed and constructed.

E. Design and some construction has been done on a button switch selection and interrupt box for computer data taking and handling. The role of the individual switch is under software control.

F. The cell and canal heater controls of the polarized ion source were rebuilt and two commercial thermocouple readouts were added.

G. A controller was designed and constructed to provide for the automatic removal of the beam from the target. The unit deflects the beam off target via the switching magnet degaussing coils when the beam intensity is either too high or too low. The reset may be automatic or manual. An optional audio alert was also included.

H. A digital readout and controller was designed and constructed for the Rawson flux meters on the 20° and 30° ion source magnets. This allows the operator to select the proper ion mass from among others with comparable charge to mass charge ratios.

I. A stepping motor controller with gating by experimental signals was constructed for use with the voltage scanning on the Auger electron experiments.

J. A system to route ten signals to two sets of ten scalers was designed and constructed for polarized ion source experiments.
K. An eight channel computer driver chassis was constructed for counting room 3.

† Retired, January 1974.
‡ Transferred, April 1974.

3.2 An 8 Channel Wide Exclusive "or" Device for Multi-Parameter Experiments
J.G. Cramer and H. Fauska

In multi-parameter experiments, one sometimes needs devices to gate on the presence of one pulse and the absence of others. Two such devices with 8 input channels each were designed and constructed using TTL throughout. The devices shape the incoming pulses, wait for a small delay time and put out a reshaped pulse if none of the other (seven) input channels has received a pulse.

The devices sense multiple pulses within a two and one half microsecond time period. Both busy and single outputs are produced. Each unit is housed in a single width AEC module.

3.3 Design of a Gas Cell for Heavy Ion Reactions
R. Vandenbosch, M.P. Webb, and M.S. Zisman

A gas target cell suitable for heavy ion reactions has been designed, constructed, and tested. One of the design criteria was separation of the beam entrance and exit foils from the foil through which the detected reaction products escape from the cell. Since heavy ion beams have a high rate of energy loss, the window through which the beam passes must have reasonable heat conductivity as well as strength. In practice, this dictates the use of a metallic foil. The windows through which only the reaction products escape are not subjected to such heating and it is practical to use plastic foils which have lower atomic number and hence cause less multiple scattering.

A second design criterion was the capability to independently replace any of the window foils easily and quickly in the event of failure during a run. This was accomplished by providing O-ring seals for window plates to which foils had been previously cemented.

A perspective view of the cell is shown in Fig. 3.3-1. The triangular shape was chosen so that the reaction products could exit nearly normal to the window for the angles of most interest and concern (∼ 60°). Kinematic effects
lead to more energetic particles in the forward direction so that energy loss is less critical at smaller angles. The smallest angle which can be observed in the configuration of Fig. 3.3-1 is about 20°. The windows presently employed are a 0.7 mg/cm² Ni entrance window, a 2.1 mg/cm² Havar exit foil (where energy loss is no longer important in determining the energy and dispersion in energy for which the reaction occurs) and a 0.54 mg/cm² (0.15 mil) mylar reaction product window. The beam windows are approximately 1/4-inch diameter circles whereas the reaction product exit window is rectangular, 3/8-inch by 1-1/2-inch. These windows have been tested at 0.2 atm, and are typically used at about 0.13 atm. The cell has been tested using the 160 + 160 elastic scattering reaction whose angular distribution exhibits a great deal of structure. This structure was observable using the present cell whereas earlier measurements with a conventional cell employing a common metallic exit foil for the beam and reaction products did not reveal appreciable structure. This cell has been used for the measurements described in Sec. 10.5.

Fig. 3.3-1. Perspective view of gas target cell for heavy ion reactions shown with window plates removed. The beam exits through the hole facing you.

3.4 A γ-Ray Transmission Method for Measuring Target Thickness and Uniformity

I. Halpern and R.E. Marrs

The pion-nucleus total cross-section experiment being prepared at LAMPF (see Sec. 15) demands an accurate knowledge of the product of pion beam flux times target thickness integrated over the target area. If either the pion flux or the areal density were constant over the target area, one would have to know only the easily measured total integral of the other quantity to determine the desired integral of the product. However the pion beam flux will not have a flat profile nor can the target areal densities be expected to be perfectly uniform. It therefore becomes necessary to measure both of these functions, at least approximately, in order to determine their actual integrated product. For the purpose of measuring the target areal densities a radiographic system has been developed. This system is designed to measure the transmission of the 662 keV line from a 137Cs source to a precision of about 1% and with spatial resolution only slightly in excess of 1/8-inch. (The targets are typically 1 gm/cm² thick and 1-1/2-inch in diameter. The pion beam is expected to be about 3/4-inch FWHM.) A schematic drawing of the measuring arrangement is shown in Fig. 3.4-1. It uses an 80 mCi 137Cs source placed at the center of a
Fig. 3.4-1. Arrangement of Source, Collimators and Detector for Target-Uniformity-Gauge used for targets of total pion cross-section experiment (Sec. 15).

cylindrical lead pig 10.5-inch in diameter. The \( \gamma \)-rays are collimated through a 1/8-inch diameter hole before impinging on the targets. Gamma-rays transmitted at zero degrees are detected in a 50 cm\(^3\) Ge(Li) detector shielded by a 4.5-inch thick lead block containing a 1/4-inch diameter hole which is aligned with the hole in the lead pig. An SCA is set on the 662 keV \( ^{137}\text{Cs} \) photopeak and the output is scaled in order to determine the number of transmitted \( \gamma \)-rays. Micrometer screws are used to move the targets in the two transverse directions.

Figure 3.4-2 shows the results of a test measurement of the uniformity of a piece of 1/8-inch thick aluminum sheet with a 1/16-inch wide, 0.018 inch deep groove milled into one side. The number of absorbed \( \gamma \)-rays is plotted as a function of transverse target position. The number of transmitted gamma rays for each point is about \( 6 \times 10^7 \) and it takes about 20 minutes to accumulate them. The data plotted as open circles in Fig. 3.4-2 were obtained with the aluminum sheet next to the source pig. In order to see whether there was any significant loss of spatial resolution of the test device when it was used with low density thick targets, we repeated the test on the aluminum plate with a 3 cm thick lithium target at fixed position between the source and the aluminum sheet. It is seen from the figure that there is essentially no resolution loss and that one could be confident to pick up voids or major impurities in even rather thick targets.

In short, the results of the resolution test establish that this method of measuring target uniformity can conveniently provide a ±1% knowledge of target density variation with adequate spatial resolution. Measurements of the targets to be used at LAMPF are presently in progress.
Fig. 3.4-2. Open circles give the reduction of counts (from value without any target) as a function of position of a 1/8-inch thick aluminum test-target with a narrow 0.018-inch deep slot milled in it. The solid points give (renormalized) data for a similar measurement where a thick fixed lithium target was added to the aluminum target (see text). The open circles correspond to a longer counting time and have errors approximately the size of the plotted circles.

3.5 A Silicon Polarimeter for Measurements of Proton Polarization Produced in Nuclear Reactions


The development of a Si-polarimeter for the determination of proton polarization produced in nuclear reactions has continued during the past year and is now essentially complete. Further measurements were not required for the completion of the design of the polarimeter due to the recent differential cross section and analyzing power results reported for proton elastic scattering on Si.

Figure 3.5-1 shows a schematic diagram of a typical double-scattering experiment and illustrates some of the features of the Si polarimeter. The analyzer (second scatterer) is a 1.9 mm x 500 mm^2 circular Si(Li) detector. Second-scattered particles are stopped in the left and right E detectors which are rectangular Si(Li) detectors 8-1/2 mm x 23 mm and 1.6 mm thick. A second scattering is indicated by coincident pulses in the analyzer and either of the E detectors. If a coincidence occurs, the pulses from the two detectors are
Fig. 3.5-1. Schematic diagram of Si polarimeter.

Added together to form a total energy signal. Total energy spectra for left and right scatterings are stored separately in order to determine the asymmetry in the second scattering. The solid angle of the polarimeter is defined by a brass collimator positioned between the two side counters. Electrons are bent away from the polarimeter by permanent magnets situated in front of the defining aperture. Approximately 2 cm of lead was placed in front of the side detectors to diminish the γ-ray and neutron background emanating directly from the target. The entire assembly rests on a carefully aligned thermoelectric cooling stand. At lower temperature, the noise of the system is reduced resulting in improved time and energy resolution. The second scattering angle is nominally 157° ± 9° and was chosen to maximize the efficiency-analyzing power product \( A^2 \omega \). The solid angle of one of the E detectors is then about 0.17 \( \text{sr} \), while the solid angle of the polarimeter itself is about 8 m\( \text{sr} \).

In Fig. 3.5-2 is shown a typical summed energy spectrum obtained with 12 MeV protons incident on a Au target. The large peak at the high energy end of the spectrum is from elastic scattering on Au followed by elastic scattering from Si. The small peak at lower energy corresponds to inelastic excitation of \(^{28}\text{Si}\). This spectrum was obtained with the requirement that an energy of at least 6 MeV be lost in the side detector. This results in an analyzing power of approximately 0.45 and is roughly constant over an incident energy range of 11-16 MeV. With such energy requirements on the side detectors, the efficiency of the polarimeter is energy dependent, being usually around 1 or \( 2 \times 10^{-5} \).
The electronics which has been incorporated into the polarimeter system includes pile-up rejection and operates easily at $10^5$ cts/sec. This gives a net counting rate to the side detectors of 1 or 2/sec. Probably the most unique feature of this polarimeter is the relatively thick analyzer detector. Since the side detectors are in reflection geometry, the analyzer used is a "stopping" detector and the singles spectrum entering the polarimeter is monitored directly.

The Si-polarimeter is currently being used to measure the depolarization parameter for the elastic scattering of protons from $^9$Be (see Sec. 9.2 of this report).


3.6 Silicon Detectors

S. Kellenbarger

In the 1973 Annual Report we mentioned making Si(Li) detectors for the "sideless" mounts. We also wanted to make surface barrier detectors for these mounts to use with heavy ions, but had difficulty since it was desired to keep the non-sensitive border of the detector as narrow as possible. Now we are mounting the surface barriers in a piece of circuit board and screwing this to the case of the detector mount in place of the aperture plate. An opening slightly larger than the detector is cut in the circuit board, and the detector mounted in this opening with Dow Corning 3140 RTV silicone rubber. Then p-type epoxy is applied to the border of the detector on the face side. Gold is evaporated on the face (extending over the p-type epoxy and onto the copper of the circuit board), and aluminum is evaporated on the back. The signal wire is epoxied to the aluminum side. The width of a detector case is 12 mm; the width of the sensitive area of a detectors is typically 7-8 mm.

In addition to detectors for sideless mounts, we are continuing to manufacture conventional Si(Li) detectors for general use. These detectors turn out to have rather stable properties; seventeen Si(Li) detectors made in 1970 and 1971 are still giving good service. These detectors have been used in 5 to 30 runs each, a run lasting an average of 2-1/2 days.

2. Epoxylite resin No. 69 and catalyst C-323, Epoxylite Corp., Box 3397, So. El Monte, CA 91733.
3. ENT-105, Chomerics, Inc., 77 Dragon Court, Woburn, MA 01801.
4. THE COMPUTER AND COMPUTING

4.1 Computer System Improvements

N.R. Cheney

A. Disc Memory Addition

A 262 K word (24 bit word) disc memory has been installed in the Laboratory’s off-line computer system. The addition of this unit has improved the speed and flexibility of the off-line computer for general computing and in the preparation of data collection programs for the on-line computer. The unit was made available to us by Xerox Corporation.

B. Incremental Plotter

The Calcomp Model 555 incremental plotter described in the 1973 Annual Report\(^1\) has been installed in the off-line computer system and is working satisfactorily.

C. Analyzer Interface

The pulse height analyzer interface to the on-line computer described in the 1973 Annual Report\(^1\) has been completed and has performed satisfactorily in the several experiments that use it.


4.2 Improvement of an On-Line Computer Program for Particle Identification with the Computer Memory Extension

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

There are a number of on-line programs in the Laboratory that use 2 ADC's to do particle identification (PID). One of them is PID which employs two $\Delta E, E$ detector arrays. PID is done by table look-up based on the range-energy formula $R = a(E)X$. The PID algorithm used is $(\Delta E+E)^X -(E)^X$.

It was found that this program was inadequate for identification of both heavy ions and high-energy light particles (when the energy deposited in the $\Delta E$ detector is small enough to create digitization effects). To correct these problems, a new parameter has been added and the PID look-up table size has been increased from 255 to 4096 channels for each system.

With the additional parameter, suggested by W. Wharton, we redefine $PID = (\Delta E+E+B)^X -(E+B)^X$. This is especially useful for heavy ion experiments since PID calculated with the latter algorithm can be made very nearly energy independent over a wide energy range. The PID table can be expanded because of
the recently available computer memory extension. The use of the memory extension is described in the SDS 930 Computer Reference Manual (pages 4 and 19). It is done by setting the extension register (EM2 or EM3) to the block of memory extension used. In the present program only EM3 was used. Care had to be taken to make sure the block switched away contains only data, not program operations. Following is the part of the program using this feature:

```
DIMENSION IDATA(4096)
COMMON IDATA

S LDA = 0620240
S STA IB34
S LDA = 0620230
S STA IB33

S EXU IB34

(CALCULATE PID TABLE)

S STA 030000,2
S EXU IB33

S LDA IAE
S ADD IE
S CAX
S EXU IB34
S LDA 03000,2
S LDX IE
S SUB 03000,2
S EXU IB33

/SET BLOCK 3 FOR DATA STORAGE ONLY, SO THAT NO OPERATION CAN BE SWITCHED AWAY.

/ASSIGN IB34 AS THE OPERATION TO SET EM3 TO BLOCK 4
/IB33 IS THE OPERATION TO SET EM3 BACK TO BLOCK 3 FOR NORMAL OPERATION

/SET EM3 EQUAL TO 4.

/STORE THE PID TABLE IN BLOCK 4.
/SET EM3 BACK EQUAL TO 3.

/BEGINNING TO DO PID TABLE LOOK-UP
```

A PID expansion and shifting option has also been added to the program in order to have the relevant part of the PID spectrum cover the whole ID table range. Other new features are the 2-dimensional line printer plot which is useful for finding the PID parameters and the addition of one ADC to the program for singles data taking. The latter ADC can be used, for example, for a monitor spectrum.

4.3 Revised Version of the Nuclear Kinematics Program HEEWEE

B. Cuengco, H. Swanson, and M.S. Zisman

A revised version of the nuclear kinematics program HEEWEE (written at this Laboratory some years ago) has been written. The major improvements in this version include the option to input parameters from the teletype as well as from cards, the addition of the complete 1972 Mass Table so Q-values need not be calculated, and the addition of several new output options such as calculation of energy losses in absorber foils and calculation of magnetic rigidities of outgoing particles (in anticipation of future magnetic spectrometer experiments).

A new input format has been chosen which is similar to the KINMAT code (originally written at Stanford and modified for the XDS-930 by H. Swanson). A reaction is now specified by writing it out, e.g., $^{12}$C($a,d)^{14}$N is obtained by typing Cl2(A,D)N14. This version will replace the old HEEWEE on the disk in the near future.

4.4 Program for On-Line Data Collection and Computer Control of an Electron Analyzer

H. Wieman

A program has been written to permit rapid data collection and analysis using a dispersive electron analyzer and gas jet target system. The program controls the voltage on the electron analyzer via a digital to analog converter and electron spectra are collected in a multi-scale mode using the Laboratory's computer-interfaced 20 MHz scalers. Simultaneous data collection with an ADC is also permitted. The program accomplishes immediate reduction of the electron data to double differential cross sections making corrections for the analyzer efficiency, geometry of a gas jet target, electron detector dark current and continuum background.

1. Section 14 of this report.

4.5 HOP-TWO: A Small-Computer Optical Model Code for Heavy Ion Elastic Scattering

J.G. Cramer

The study of heavy ion elastic scattering has produced a need for a small-computer optical model code which is capable of handling a large number of partial waves and a large number of angular points in an angular distribution, and facilitating comparisons between calculations and data. A new optical model program, HOP-TWO, has been developed. It bears some resemblance to its predecessors OP of Fernandez and LOP of Shaw, both written at this Laboratory. It differs from these programs in that it uses fast Numerov integration of the Schrödinger
equation, the Wills Coulomb function routine, and can calculate up to 200 partial waves (160 partial waves is the practical limit because of the limitations of the Coulomb wave function subroutine) and up to 300 angles. It has a simplified input format with many default options, accepts experimental data and calculates a $\chi^2$ for the data vs. calculation, can renormalize the data based on the first n data points, produces a 4-cycle high-density plot of the data and calculation in ratio-to-Rutherford, and plots at high density an Argand diagram of the scattering matrix. The program includes options for identical particles, for many standard forms of potentials, can use an externally generated potential read in as a table, and can use an arbitrarily large number of integration steps by interpolating its internal potential table. This code has been in successful operation for almost a year at this Laboratory on the SDS-930 computer system and a slightly modified version is in operation on the Universität München PDP15 computer system. Modified versions are under development which will permit fast parameter searching with analytical computation of derivatives in the integration loop and exact treatment of non-local potentials.

1. Section 10.6 of this report.
3. J.C. Wills, private communication.

### 4.6 Heavy Ion Optical Model Calculations with Approximate Non-Local Potentials

J.G. Cramer

A new version of the heavy ion optical model code HOP-TWO, version 2.8, has been written to include approximate non-local optical potentials. This program has been used to investigate non-local effects in heavy ion scattering, and such effects have been found to be surprisingly strong, in that a non-locality range $\delta$ of as little as 0.2 fm can produce marked changes in the equivalent local potential and in angular distributions. Consideration of the approximations used makes it clear why non-locality effects should be particularly important for heavy ion reactions.

The prescription given by Perey and Buck for generating an equivalent local potential $U_L(r)$ from a non-local potential $U_N(r)$ for the case of neutron scattering is:

$$U_L(r) = U_N(r) \exp\left[-\frac{(\delta k)^2}{2(1 - \frac{U_L(r)}{E_{cm}})}\right]$$  \hspace{1cm} (1)$$

where $k$ is the wave number, $E_{cm}$ is the center of mass energy, and $U_L(r)$ are the full complex nuclear potentials. It is suggested that (1) can be iterated to generate $U_L$ from $U_N$ and that the potentials thereby generated give surprisingly accurate predictions of non-local effects. However, it should be noted that the iteration of (1) will converge only for $|(\delta k/2)^2 U_L/E_{cm}| < 1$. 27
To treat the case of heavy ions it was necessary to include the Coulomb potential, which was omitted in the derivation of (1) and also devise a procedure for generating \( U_L \) when \( |(3k/2)^2 U_L/E_{cm}| > 1 \), a condition to be expected due to the large values of \( k \) encountered in heavy ion reactions.

The approximations which have been used in the present calculations are

\[
U_L(r) = U_N(r) \exp[-\alpha(\varepsilon - U_L)] \quad \text{for} \quad |\alpha U_L| < 1
\]

and

\[
U_L(r) = \frac{1}{\alpha} \ln\left(\frac{U_L}{U_N}\right) + \varepsilon \quad \text{for} \quad |\alpha U_L| \geq 1
\]

where \( U_L(r) = U_L(r)/E_{cm} \),

\[
U_N(r) = U_N(r)/E_{cm}, \quad \alpha = \left(\frac{3k}{2}\right)^2,
\]

and \( \varepsilon(r) = 1 - V_{\text{Coul}}(r)/E_{cm} \) with

\( V_{\text{Coul}} \) the usual Coulomb potential. In the program, the complex Woods-Saxon potential \( U_N \) was evaluated, \( U_N, \varepsilon, \) and \( \alpha \) were calculated, and a starting value of \( U_L \) which we will call \( U_L^0 \) was assumed according to:

\[
U_L^0(r_1) = \frac{1}{2} U_N(r_1)
\]

\[
U_L^0(r_n) = U_L(r_{n-1}) \quad \text{for} \quad n > 1,
\]

i.e., the last value of \( U_L(r) \) calculated was used as the starting value for the next radial step. The value of \( |\alpha U_L^0| \) was then calculated and either (2) or (3) was iterated to give \( U_L(r) \) which was then substituted for \( U_N(r) \) in the potential table used in the calculation.

From this point the calculation proceeded as a normal optical model calculation.

Figure 4.6-1 illustrates the effect of using approximate non-locality on a typical heavy ion potential \( V = 100 \) MeV, \( W = 44.2 \) MeV, \( r_0 = 1.06 \) f, \( a = 0.64 \) f with the non-local range \( \beta \) varied between 0 and 1.0 f. As shown, the inclusion of non-locality produces in the equivalent local potential \( U_L(r) \)

\[
\text{Fig. 4.6-1. Effect of non-locality on real and imaginary Woods-Saxon potentials with } V_0 = 100 \text{ MeV, } W_0 = 44.2 \text{ MeV, } r_0 = 1.06 \text{ f, } a = 0.64 \text{ f. Solid curves show equivalent non-local potential for various values of the non-locality range } \beta. \text{ Dashed curves show Woods-Saxon potentials fitted to these in the surface and tail region.}
\]
a large decrease in the magnitude of the potential and also results in a potential
with a distinctly non-Woods-Saxon shape. However, fitting $U_p$ with a Woods-Saxon
potential matched to the surface and exterior region (the regions of importance
in heavy ion scattering) permits us to estimate the effect of non-locality on the
Woods-Saxon parameters. We see that the diffuseness parameter $a$ is unaffected by
non-locality, while the potentials $V$ and $W$ are strongly decreased and the radii
$r_p$ and $r_f$ are strongly increased by the inclusion of non-locality. These effects
are expected to be energy dependent, implying that both the geometry and the
depth of heavy ion potentials would be expected to have strong energy dependence
if non-locality is important and is not treated explicitly.

We plan to incorporate approximate non-locality as described above in the
search code GENOA to permit a global search of heavy ion scattering data to find
global non-local potentials, and to investigate non-local effects in DWBA calcu-
lations.

1. See Sec. 4.5 of this report.
3. F.E. Hodgson, The Optical Model of Elastic Scattering, Sec. 3.2, Oxford

4.7 Polarization Data-Collection Program

T.A. Trainor

A data-collection program POLSING has been written for use in conjunction
with polarized proton beam experiments. This program stores spectra in 4096
words divided into two 2048 word data blocks corresponding to proton spin up and
down on target. Provision is made to interrogate polarized ion source controls
through an external sense line to determine the spin direction and store events
in the appropriate data block. The program is used with up to three detector
pairs plus beam polarization monitor and beam intensity monitor detectors.
Analyzing powers, instrumental asymmetries and total yields for each detector
pair, as well as the beam polarization are continuously updated during data col-
lection and displayed on nixie tube arrays. Provision is made for transferring
peak-sum windows from one data block to the other so that peak summing is the
same for both spin directions. With these provisions complete on-line analysis
of proton-polarization data is possible.

4.8 SCOSINDHAP/SCOSINEAP: Data Collection/Analysis Program for Coincidence
Experiments

J.E. Russoletti and R.E. Marris

Two computer programs intended specifically for use in branching ratio
measurements but designed to be sufficiently general for any type of dual coinci-
dence experiment have been completed and rigorously tested this past year.

SCOSINDHAP (Simultaneous Coincidence and Singles Data Handling Program)
is the data collection program. Its features include: a) the ability to simultaneously collect singles and coincidence data through the same ADC with the aid of one external OR logic circuitry; b) storage of up to three types of signals (TAC, E1, E2); c) event recording of coincidence data available as an option; d) on-line one dimensional display of all data on either of the two CRT's; e) two digital windows may be defined on the TAC spectrum for on-line sorting of E1 and E2 coincident data; f) up to 16 digital bins may be defined on the E1 spectrum for on-line sorting of E2 coincident events; f) the lengths of the event recording buffer and the on-line display buffer are variable, subject to two constraints: EVENT + ARRAY = 5160 and EVENT ≤ 3062 (the event buffer is dumped automatically when full); h) to facilitate set-up of experiments, the program may be operated entirely in the conventional mode in which singles spectra accumulate from all ADC's; i) any signal may be routed by using the external routing system; j) a monitor spectrum, always operating in the singles mode, may be accumulated if desired.

The simultaneous nature of the accumulation of singles and coincident spectra is the feature of the program which is particularly desirable for branching ratio measurements. It guarantees equality in signal processing for the two signals and eases considerably the later analysis of the data by guaranteeing matched gains and intercepts in the final spectra. Additionally, only one period of accelerator time is required to accumulate both singles and coincidence spectra. The simultaneous singles spectrum can be any of the three signals: TAC, E1 or E2. The only external requirement is that the SINGLES PRESENT logic signal be applied through an OR logic circuit with the COINCIDENCE PRESENT logic signal to the EVENT OCCUR interrupt of the computer. The computer checks a format register internally to determine the character of the event. Since singles signals generally occur at a high rate, the singles logic signal is usually divided externally by some power of 10 before being applied to the OR gate. A typical electronics set-up for simultaneous singles data collection is shown in Fig. 4.8-1.

SCOSINEAP is an acronym for Simultaneous COincidence and SINGles Event Analysis Program. This program was written to perform off-line analysis of the event recorded tapes generated by SCOSINDHAP, but can also analyze tapes generated by the program TAPAL (see Sec. 5.3 of last year's report).

The analysis program will sort data into either one dimensional spectra or two dimensional spectra. When sorting in the 1D mode, up to two windows on one spectra and two windows on a second spectrum may be specified for the sort. When sorting in the 2D mode, the axes of the spectrum may be any pair of the three choices TAC, E1 and E2, and a window may be placed on the remaining spectrum. The 2D plot is limited to a 64x64 region due to core restrictions; the program allows sorting of uncompressed data into 64x64 sections or compresses data by some specified power of two and stores compressed spectra into a 64x64 block.

Additional utility programs are available for tape editing, plotting, and spectrum summing/differencing.
4.9 Lineshape Fitting Program for the 10\(^\text{th}\)×10\(^\text{th}\) NaI Spectrometer

R.E. Marrs

A non-linear, least squares fitting program has been written for analyzing spectra from the 10\(^\text{th}\)×10\(^\text{th}\) NaI spectrometer. A standard lineshape, which might come from a coincidence measurement or from some other source, is entered empirically for any one energy. The general shape of the standard line is assumed constant but its horizontal dimension is scaled in proportion to the \(\gamma\)-ray energy in order to fit peaks of different energy in the spectrum. Provision is also made for entering an arbitrary background, which underlies the least squares generated fit.

During the fitting process the peak positions are determined by a grid search method, and the peak amplitudes are determined by a linear least squares fit using a matrix inversion. The fitting procedure is iterated until convergence is obtained within specified limits. The program runs on either of the XDS 930 computers and will provide a CRT display of both the data and the fit if computer #1 is used.
4.10 Program for Calculation of Moshinsky Brackets

M.S. Zisman

A program PHYL which generates tables of harmonic oscillator transformation brackets ("Moshinsky Brackets") has been modified to run in Fortran II on the XDS-930 computer. Rather than use the somewhat cumbersome recursion formulae outlined by Brody and Moshinsky, the code utilizes a closed-form expression derived by Barber and Cooper. This allows the program to be relatively concise and easily adaptable as a subroutine for other types of calculations such as the examples given below.

2. A. Barber and B.S. Cooper, Nucl. Data A 10, 50 (1971).

4.11 Program for Calculation of Two-Particle Central Matrix Elements

M.S. Zisman

A shell-model code PHYLLIS which calculates two-particle central force matrix elements of the residual interaction has been modified to run in Fortran II on the XDS-930 computer. The method of calculation is that outlined by Brody and Moshinsky. A two-particle harmonic oscillator wave function is expanded by means of Moshinsky brackets into relative and center of mass coordinates. The residual interaction matrix elements can then be expressed as a sum of Talmi integrals which, for a Gaussian force, can be obtained in closed form. Calculations of this type are useful for estimating the excitation energy of a particular two-particle configuration which might be populated in a two-nucleon transfer reaction, for example.


4.12 Program to Calculate Two-Nucleon Transfer Structure Factors

M.S. Zisman

A Fortran II program G-FACTOR has been written to calculate Glendenning's structure factors for two-nucleon transfer reactions. The program allows the user to select a harmonic oscillator parameter (which can be chosen to be consistent with available shell model calculations) and then generates a table of structure factors for a given oscillator shell for any of the three reactions.
(p,t), (p,^3He), or (a,d). The format of the table is similar to that used by Glendenning.²


4.13 Data Analysis Program "2D RERANAL"

J.W. Tape

A program has been written for the XDS 930 computer which scans event recorded magnetic tapes generated by the on-line data taking program TAPAL (see last year's report, Sec. 5.3). TAPAL event data consists of three words for each event; time to amplitude (TAC), energy "one" (E1), and energy "two" (E2) information. "2D RERANAL" reads the event tapes using an XDS routine MTAPE which is faster than the conventional FORTRAN binary tape reading routines, and sorts the data into two-dimensional (56×56 channels) arrays of E1 vs E2 according to "real plus random" and "random" digital windows on the TAC spectrum. Randoms are subtracted and the resulting arrays written on tape and output to the line printer. A second program projects the data onto either the E1 or E2 axes and plots the resulting spectrum.

4.14 An Improved Set of Subroutines for the Calcomp Plotter

L. Baker, J.G. Cramer, and T.A. Trainor

The Calcomp Incremental plotter mentioned in Sec. 4.1 of this report has been in use for about 4 months, and a set of systems programs has been developed to facilitate its use in data plotting and general graphics applications. These programs are based on the Bausch and Lomb plotter programs obtained from the XDS Users Library, but have been considerably expanded and improved. The principal improvements, aside from correcting several errors and 930 incompatibilities in the original programs, were to add subroutine POINT for plotting points with error bars and to greatly expand and improve the character subroutine SYMBOL.

Subroutine POINT plots eight different plotting symbols with or without error bars and in a variety of sizes and orientations.

Subroutine SYMBOL originally plotted 47 standard symbols, i.e., the 10 numbers, 26 upper case letters and 11 special symbols. To this have been added the 26 lower case letters, 19 upper and lower case Greek letters most commonly used in physics applications, and the special symbols set has been expanded to 32. Moreover, capabilities for shifting between upper and lower case, backspacing, and easy superscript and subscript generation have been added. Further, each character now has its own space value so that small letters are closely spaced while more space is allowed for wider characters. The character set was designed to resemble as closely as was feasible the style of Leroy-type letters used by professional draftsmen. The result is high quality lettered text which resembles set type or professional lettering. Figure 4.14-1 shows the complete
Calcomp character set.

These systems have now been added to the FORTRAN II and REAL-TIME FORTRAN libraries on the off-line computer disc and tape operating systems.

4.15 A General Table Generation Program for the Calcomp Plotter

J.C. Cramer

It is frequently desirable in preparing talks and papers to generate tables of numbers or sequences of equations, reactions, etc. A program named TABLE has been written for use in transforming punch card input into neatly lettered tables of numbers, words, symbols, etc. The program includes facilities for 14 tabulation positions, changes in character size and line spacing, and all the features of subroutine SYMBOL described in Sec. 4.14, including superscript and subscript generation. Figure 4.15-1 shows an example of a table prepared with this program.

<table>
<thead>
<tr>
<th>BCD CODE</th>
<th>UPPER CASE</th>
<th>LOWER CASE</th>
<th>KEYPUNCH CODE</th>
<th>PUNCH CODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>0</td>
<td>α</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>01</td>
<td>1</td>
<td>β</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>02</td>
<td>2</td>
<td>γ</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>03</td>
<td>3</td>
<td>δ</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>04</td>
<td>4</td>
<td>ε</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>05</td>
<td>5</td>
<td>ζ</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>06</td>
<td>6</td>
<td>η</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>07</td>
<td>7</td>
<td>θ</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>08</td>
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<td>8-15</td>
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<td>(V)</td>
<td>8-20</td>
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<td>(W)</td>
<td>8-21</td>
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<td>(Y)</td>
<td>8-23</td>
<td></td>
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<tr>
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<td>z</td>
<td>(Z)</td>
<td>8-24</td>
<td></td>
</tr>
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</table>

0 indicates normal shift of the keyboard.

Figure 4.14-1.
# Angle Shifts Observed in $^{16}\text{O}, \text{^{15}N}$ Reactions on F-P Shell Targets

<table>
<thead>
<tr>
<th>Residual Nucleus</th>
<th>$\Delta \theta$</th>
<th>$Q$ MeV</th>
<th>$Q_{opt}$ MeV</th>
<th>$\Delta Q$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{41}\text{Sc}(7/2^-)$</td>
<td>$+11^0$</td>
<td>$-11.05$</td>
<td>$-2.78$</td>
<td>$8.26$</td>
</tr>
<tr>
<td>$^{43}\text{Sc}(7/2^-)$</td>
<td>$+2^0$</td>
<td>$-7.20$</td>
<td>$-2.82$</td>
<td>$4.38$</td>
</tr>
<tr>
<td>$^{45}\text{Sc}(7/2^-)$</td>
<td>$0^0$</td>
<td>$-5.23$</td>
<td>$-2.86$</td>
<td>$2.37$</td>
</tr>
<tr>
<td>$^{47}\text{Sc}(7/2^-)$</td>
<td>$0^0$</td>
<td>$-3.65$</td>
<td>$-2.89$</td>
<td>$0.76$</td>
</tr>
<tr>
<td>$^{49}\text{Sc}(7/2^-)$</td>
<td>$0^0$</td>
<td>$-2.50$</td>
<td>$-2.93$</td>
<td>$-0.43$</td>
</tr>
<tr>
<td>$^{47}\text{V}(7/2^-)$</td>
<td>$-5^0$</td>
<td>$-7.10$</td>
<td>$-3.04$</td>
<td>$4.06$</td>
</tr>
<tr>
<td>$^{51}\text{V}(7/2^-)$</td>
<td>$-2^0$</td>
<td>$-4.07$</td>
<td>$-3.10$</td>
<td>$0.97$</td>
</tr>
<tr>
<td>$^{53}\text{Mn}(7/2^-)$</td>
<td>$-4^0$</td>
<td>$-5.56$</td>
<td>$-3.26$</td>
<td>$2.30$</td>
</tr>
<tr>
<td>$^{55}\text{Mn}(7/2^-)$</td>
<td>$-7^0$</td>
<td>$-4.06$</td>
<td>$-3.29$</td>
<td>$0.77$</td>
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<tr>
<td>$^{57}\text{Co}(7/2^-)$</td>
<td>$-10^0$</td>
<td>$-7.07$</td>
<td>$-3.95$</td>
<td>$3.12$</td>
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<tr>
<td>$^{59}\text{Co}(7/2^-)$</td>
<td>$-11^0$</td>
<td>$-6.10$</td>
<td>$-3.41$</td>
<td>$2.69$</td>
</tr>
<tr>
<td>$^{59}\text{Co}(7/2^-)$</td>
<td>$-8^0$</td>
<td>$-4.75$</td>
<td>$-3.44$</td>
<td>$1.31$</td>
</tr>
</tbody>
</table>

$\Delta Q = Q_{opt} - Q$

$Q_{opt} = E_{cm} \left[ (Z_f Z_f / z_1 z_1) - 1 \right]$

from Körner, Morrison, Greenwood, and Siemssen,
*Phys. Rev. C* 7, 107, (1973)

Fig. 4.15-1. Example of Table Made with Table Generation Program.
4.15 Evaluation of Finite-Geometry Corrections in Double-Scattering Measurements

M.P. Baker and W.G. Weitkamp

A FORTRAN program has been written to calculate finite-geometry corrections for double-scattering measurements (see Sec. 9.2 of this report). Such corrections arise because of the angular dependence of the differential cross section and analyzing power in the first scattering and because the finite heights of the defining apertures allow the detection of events which are "out-of-plane".

The program establishes a grid of points on the apertures which define the first and second scatterings and determines the scattering trajectories for each combination of grid points. Available scattering data are interpolated in energy and angle to yield values for the differential cross sections and analyzing powers appropriate to each trajectory. The number of events detected after the second scattering is then calculated for each trajectory and a sum over all the trajectories is determined separately for each of the second scattering detectors. The program includes an option for cases where the incident beam is polarized. In those cases, a full description of the double-scattering process requires that data for the Wolfenstein or "triple scattering" coefficients also be given as input.
5. LEVELS IN LIGHT NUCLEI

5.1 Further Study of High-Lying Levels in $^5$He

Y.D. Chan, J.G. Cramer, B. Cuengo, K.L. Liu, and M.S. Zisman

The high-lying levels in $^5$He have previously been studied with the $^7$Li(d,$\alpha$)$^5$He reaction at 24 MeV. This experiment has been repeated with a thinner $\Delta E$ detector to look for even higher excited states. The results obtained are shown in Fig. 5.1-1. The carbon and oxygen contaminant backgrounds have been subtracted by means of a monitor normalization. The spectrum after many-body phase space subtraction is shown in the inset. The 24 MeV state observed in the previous experiment was easily visible. Unfortunately, the 19.6 MeV state seen previously was obscured by a state in $^6$He from the $^7$Li(d,$^3$He)$^6$He reaction due to our inability to separate $\alpha$'s from $^3$He's with the particle identification method used.²

At higher excitation energy, there seems to be a peak corresponding to a state of about 28 MeV. However, the asymmetric shape of this peak suggests that it more likely comes from the breakup of the $^8$Be 11.4 MeV state populated by the $^7$Li(d,n)$^8$Be reaction. Such a breakup peak has been observed for the 18.6 MeV $^8$Be state from the same reaction. The three body kinematics show that indeed this is the peak shape it will produce, i.e., a steep shoulder on the low energy side and a tail on the higher energy side.

On the other hand, the observed state does not fit very well with the kinematics of this breakup. In Fig. 5.1-1, the arrow shows where the kinematics predict the $^8$Be 11.4 MeV breakup peak should be. Unfortunately lack of a calibration point at such low energy prohibits us from putting much weight on this argument.

Another explanation for this peak shape is that the peak is actually a superposition of two $^5$He states, a narrow one at higher excitation energy and a wide one at lower excitation energy. This seems to agree better with the kinematic calculations, as can be seen in Fig. 5.1-2. However, it seems clear that
a coincidence experiment will be required to clean up the many-body phase space background. Thus it is hard to draw any firm conclusions at present.

2. See Section 4.2 of this report.

5.2 Isospin Forbidden γ-Decays of the Lowest T = 3/2 Level in 13C

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

Prior to this work only a small fraction (≈38%) of the total isospin forbidden decay width of the lowest T = 3/2 level of 13C was accounted for (see Ref. 1). The overwhelming majority in case the calibration is incorrect of this decay was neutron emission to the 4.44 MeV state of 12C. We have studied the isospin forbidden α-decay via coincidence techniques. The 13C T = 3/2 level was populated in the 11B(3He,p) reaction at a bombarding energy of 5.3 MeV. Protons were detected at 0° in a telescope consisting of a 30° surface barrier detector and a 2 mm silicon detector. Nickel and aluminum foils of 16 mg/cm² total thickness were placed in front of the telescope to stop the incident 3He beam. Since the 11B(3He,α) reaction produces a strong coincident background a crude form of particle ID was used which consisted of an SCA placed on the region of the 30° detector spectrum containing the proton group of interest. The α-detector was a 200° surface barrier counter placed at 49° in the laboratory. Data was recorded by event as described in Sec. 5.2 of this report. A very large number of decays to channels resulting in α-particles was observed. However the interpretation of the coincident α-spectrum is difficult because all levels in 9Be except the ground state decay into 2α+n. Therefore most "decay" α's are accompanied by two "breakup" α's. For the low lying relatively narrow levels of 9Be one can distinguish the decay α group because it is comparatively "sharp". Sizable branches were observed to states in 9Be at Eα = 0.0, 1.67, and 2.43 MeV. A somewhat weaker branch to the 3.03 MeV level is present and in addition a strong continuum was observed. Analysis is continuing but the branches to the discrete states alone will not be sufficient to account for the missing width of the
5.3 Isospin Forbidden Proton Decays of the Lowest T = 3/2 Level in $^{13}\text{N}$

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

Prior to this work only $\lesssim 60\%$ of the isospin violating decay width of the lowest T = 3/2 level in $^{13}\text{N}$ was identified. The observed branches were p-wave proton decays to the ground, 4.44 and 7.65 states of $^{12}\text{C}$ and $\alpha$-decays to the ground 1.5 and 2.33 MeV states of $^{9}\text{B}$. We have directed our attention to previously unobserved proton decays of the T = 3/2 level to the 9.63 (3$^-$), 10.84 (1$^-$) and 12.71 (1$^+$) states of $^{12}\text{C}$, see Fig. 5.3-1 for a level diagram.

Recently Braithwaite et al. made a study of the isospin mixing between the 12.71 (T = 0) and 15.11 MeV (T = 1) $J^m = 1^+$ states of $^{12}\text{C}$. They interpreted their results in terms of two state mixing with an isospin intensity admixture of $0.011 \pm 0.004$. Such a large T = 1 admixture into the 12.71 MeV state should produce a significant proton branch to this state since the lowest T = 1 state of A = 12 should be a strong parent of the lowest T = 3/2 level of A = 13. We estimate the proton decay width to the 12.71 MeV state as follows:

$$\Gamma_p = \frac{2\gamma^2_{WL}C^2S}{P}$$

where $P$ is a Coulomb penetration factor, $\gamma^2_{WL}$ is the Wigner limit, $C^2$ is the square of an isospin vector coupling coefficient and S is a spectroscopic factor.

If we assume $S = 0.011 \pm 0.004$ we find an estimated width $\Gamma_p = (0.14 \pm 0.04)$ keV. Using previously known quantities, plus the $\gamma$-ray branching ratio of the T = 3/2 level to the $^{13}\text{N}$ ground state described elsewhere in this report we find $\Gamma_{TOTAL} = (0.77 \pm 0.15)$ keV. Therefore one expects a fairly sizeable branch to the 12.7 MeV state of $^{12}\text{C}$. However the decay protons have only 378 keV in the CM system so they are hard to see directly. But we can observe the branch by detecting the 12.7 MeV de-excitation $\gamma$-rays. Because of the small $\gamma$ $(2.5 \pm 0.3)\%$ branching ratio for $\gamma$-ray emission the expected number of 12.7 MeV gamma rays from the proton decay to the 12.7 MeV state compared to the 15.1 MeV $\gamma$'s from EM decay to the $^{13}\text{N}$ ground state is $(15.0 \pm 6.2)\%$.

However as was noticed previously an ambiguity is involved (see Fig. 5.3-1). The 12.7 MeV gammas can come from proton decays to the 12.71 MeV state or from $\gamma$-decays to the 1/2$^+$ state in $^{13}\text{N}$ at 2.37 MeV. To identify which of these processes produces the 12.7 MeV gamma rays we studied the decays of the corresponding T = 3/2 levels in $^{13}\text{C}$ and $^{13}\text{N}$. If the 12.7 gamma ray is produced by $\gamma$-decay to the 1/2$^+$ level it should be present with equal strength in $^{13}\text{C}$ and $^{13}\text{N}$ (corresponding $\Delta T = 1$ $\gamma$-decays in mirror nuclei are identical in all respects if isospin is a good quantum number). On the other hand if the 12.7
Fig. 5.3-1. Level diagram for the isospin forbidden particle decays of the lowest $T = 3/2$ levels of $^{13}\text{C}$ and $^{13}\text{N}$.

MeV $\gamma$ comes from proton decay to the 12.7 MeV state of $^{12}\text{C}$ it should not be observed in $^{13}\text{C}$ since n decay of $^{13}\text{C}$ to the 12.7 MeV state is energetically impossible. We have studied the $\gamma$-rays from the decay of the lowest $T = 3/2$ levels in $^{13}\text{C}$ and $^{13}\text{N}$ using coincidence techniques (see Sec. 5.2 of this report) and see $\gamma$-rays in $^{13}\text{C}$ corresponding to the E1 transition to the $1/2^+$ level. We observe $\Gamma_{\text{E1}}(^{13}\text{C}) = (4.45 \pm 0.78)$ eV from this we expect $\Gamma_{\text{E1}}(^{13}\text{N}) = (5.2 \pm 0.9)$ eV due to E1 decays alone. We actually observe a branching ratio in $^{13}\text{N}$ equivalent to $(^{13}\text{N}) = (3.2 \pm 0.9)$ eV (where the error is based on a formal analysis only). Thus there is no sign of extra 12.7 MeV $\gamma$'s in $^{13}\text{N}$ which could be ascribed to proton decays to $^{12}\text{C}(12.71)$. A crude upper limit on this branch is $\approx 1/3$ of that expected on the basis of the reported isospin mixing in $^{12}\text{C}$. At present we are planning to take more data on the $^{13}\text{N}$ decays since the yield of 12.7 MeV $\gamma$'s is not very well determined by our present results. The additional results will allow us to establish a better limit on p decays to the 12.7 MeV state.

We studied the proton decays to the 9.53 and 10.84 MeV states of $^{12}\text{C}$ using the $^{11}\text{Be}(^{3}\text{He},np)$ reaction. We detected the decay protons in coincidence with neutrons populating the level in a fashion similar to Ref. 1 except that
an event by event data collection program was employed. The proton detector was a 200 μ surface barrier detector followed by a 3 mm Li drifted detector. The detectors were preceded by a foil thick enough to stop all α's from the decay of $^{13}_N(T = 3/2)$.

Data was analysed as a two dimensional array of neutron flight time vs proton energy. Sums along the kinematic loci corresponding to $^{12}_C$ in its various excited states, project onto the flight time axis, are shown in Fig. 5.3-2. Decays to $^{12}_C$ states at 0.0, 4.44, 7.68, 9.63 and 10.84 MeV are observed. The branching ratios and corresponding reduced widths in single particle units are displayed in Table 5.3-1. It can be seen that the $s$ and $d$ wave decays to the negative parity states are much more important than the $p$-wave decays to the positive parity levels. The $s$ and $d$ wave decays arise from $p^7(sd)^2 T = 1/2$ impurities in the $T = 3/2$ level, the $p$ shell decays come from $p^9$ impurities. Why are the $p^7(sd)^2$ impurities so important in $^{13}_N$? The answer is probably that for pure $p$-shell configurations the two body Coulomb force gives essentially no isospin mixing in $^{13}_N$ since there is only one charged hole in the closed $p$-shell core. On the other hand the centroid of the $p^7(sd)^2$ strength is expected to lie relatively close to the $T = 3/2$ level and $\langle \alpha_1^2 \rangle$ Coulomb matrix elements are not inhibited.

These results demonstrate that one cannot understand the isospin mixing in the lowest $T = 3/2$ levels without including the $sd$ shell configurations in the model space. Previous microscopic calculations have assumed that the only admixture out of the $p$-shell is mixing of the isovector monopole state by the effective one body Coulomb potential. In light of our results this simplification is not realistic.

Fig. 5.3-2. Projection onto the neutron time-of-flight axis of coincidence data for the reaction $^{11}_B(3He, np)^{12}_C$. Data were taken with $E_{3He} = 7.0$ MeV, $\delta_n = 0^\circ$, $\delta_p = 123^\circ$. Spectra are shown for reactions corresponding to $^{12}_C$ in its ground, 4.44, 9.63, and 10.84 MeV states. The enhancement shown at approximately channel 240 corresponds to the lowest $T = 3/2$ level in $^{13}_N$. The ground state spectrum was obtained from a different run than the spectra leading to excited states of $^{12}_C$. 
Table 5.3-1. Isospin forbidden proton decays of the lowest \( T = 3/2 \) level in \(^{13}\text{N}\)

<table>
<thead>
<tr>
<th>( ^{12}\text{C} ) State</th>
<th>Branching Ratio</th>
<th>( \ell )</th>
<th>( \frac{\gamma^2}{\gamma^2(\text{WL})} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00 0( ^+ )</td>
<td>0.236 ± 0.012(*)</td>
<td>1</td>
<td>0.96 ( \times 10^{-5} )</td>
</tr>
<tr>
<td>4.44 2( ^+ )</td>
<td>0.150 ± 0.010(*)</td>
<td>1</td>
<td>0.82 ( \times 10^{-5} )</td>
</tr>
<tr>
<td>7.65 0( ^+ )</td>
<td>0.053 ± 0.015(*)</td>
<td>1</td>
<td>0.43 ( \times 10^{-5} )</td>
</tr>
<tr>
<td>9.63 3( ^- )</td>
<td>0.096 ± 0.014</td>
<td>2</td>
<td>3.4 ( \times 10^{-5} )</td>
</tr>
<tr>
<td>10.84 1( ^- )</td>
<td>0.164 ± 0.036</td>
<td>0</td>
<td>2.2 ( \times 10^{-5} )</td>
</tr>
</tbody>
</table>

\(*\) from Ref. 1.

\( \gamma^2 = \frac{\Gamma_{\text{lab}}}{2P_{\ell} P_{\text{L}}} \) calculated at \( R = 1.4(1 + 1/3) \) \( \text{fm} \)

6. NUCLEAR ASTROPHYSICS

6.1. Production of $^6$Li, $^9$Be and $^{10}$B in the Proton Bombardment of $^{13}$C

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

Measurements have been completed of the production of $^6$Li, $^9$Be, and $^{10}$B in proton bombardment of $^{13}$C. Yields for these reactions have been studied at proton energies from near threshold up to 18 MeV, using the bunched proton beam of the tandem Van de Graaff, with time-of-flight mass identification in solid state detectors. Total cross sections for $^{10}$B production, extracted from these measurements, have been presented previously. The total cross sections for $^6$Li and $^9$Be production are presented in Table 6.1-1. These cross sections include extrapolated contributions from unmeasured regions in the (c.m.) angular and energy distributions; estimates of the uncertainties in the extrapolation are reflected in the quoted uncertainties.

Table 6.1-1. Total cross sections for the production of $^6$Li and $^9$Be in proton bombardment of $^{13}$C. The listed errors are the relative errors at each energy; in addition there is an overall normalization uncertainty of about 5%.

<table>
<thead>
<tr>
<th>Proton Energy (MeV)</th>
<th>Total Cross Sections (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^6$Li</td>
</tr>
<tr>
<td>10.9</td>
<td>5.4 ± 1.4</td>
</tr>
<tr>
<td>11.4</td>
<td>10.0 ± 1.5</td>
</tr>
<tr>
<td>12.0</td>
<td>22.5 ± 2.4</td>
</tr>
<tr>
<td>13.15</td>
<td>34.9 ± 3.9</td>
</tr>
<tr>
<td>14.0</td>
<td>41.4 ± 3.8</td>
</tr>
<tr>
<td>15.0</td>
<td>49.3 ± 3.0</td>
</tr>
<tr>
<td>16.0</td>
<td>51.3 ± 2.6</td>
</tr>
<tr>
<td>17.0</td>
<td>49.6 ± 2.3</td>
</tr>
<tr>
<td>18.0</td>
<td>45.9 ± 1.7</td>
</tr>
</tbody>
</table>

Ultimately cross sections such as those presented here should be incorporated in a model for light element production which specifies definite production mechanisms and environments, including energy spectra and initial abundances for the interacting nuclei, and in which all reactions leading to element production and destruction are followed. Jacobs et al. have investigated a more limited preliminary question: "Do the cross sections for proton reactions with the most abundant progenitors ($^{12}$C, $^{14}$N and $^{16}$O) in themselves rule out the possibility that the light elements are produced chiefly in reactions at low energy, up to several tens of MeV?" This supposition is incompatible with models for production by galactic cosmic rays in which the cosmic ray spectrum is described by a power law in total energy. However, it could be consistent with less restrictive galactic cosmic ray models, as well as with production in supernova, big bangs,
or stellar flares. If production occurs at low energies, then targets with low reaction thresholds, namely $^{13}$C (not included by Jacobs et al.) and $^{14}$N, are of particular importance.

In the analysis of Jacobs et al. a comparison was made between solar system light element abundance ratios, from a tabulation by Cameron, and ratios calculated at given energy from light element production cross sections. Abundances of $^{12}$C, $^{14}$N and $^{16}$O were assumed to be in the ratios of 3.5:1:5, in a crude approximation to the solar system values and to observed galactic cosmic ray values. Cross sections for $^{14}$N($p$,x)$^{11}$C and $^{14}$N($p$,2x)$^{7}$Be were taken from the measurements of Jacobs et al. for energies up to 22 and 24 MeV, respectively, and the remaining cross sections were taken from the extensive investigations by the Michigan State Group. (It should be noted that below 30 MeV $^{16}$O plays almost no part, and that, except for the production of $^{11}$B above 20 MeV, the $^{12}$C cross sections are small compared to the $^{14}$N cross sections.)

A more complete analysis can be made by including contributions from $^{13}$C as well. This is done for the results displayed in Fig. 6.1-1, where ratios of product abundances are shown for several different $^{13}$C/$^{12}$C abundance ratios. It is seen that the B/Li ratio, dominated by $^{11}$B and $^{7}$Li, is little affected by the presence of $^{13}$C. For any plausible $^{13}$C abundance, the observed solar system B/Li ratio can be reasonably well matched by an appropriately weighted proton spectrum, concentrated in the energy interval between 10 and 25 MeV. However, the implications of such agreement must be viewed cautiously, because the "observed" ratio is based on a high value of the B abundances, which is a matter of some controversy.

$^{13}$C has a more pronounced effect on the other ratios plotted in Fig. 6.1-1. The $^{11}$/10 ratio, which with no $^{13}$C rises very rapidly at low energies, is held to moderate values at even the normal solar system $^{13}$C/$^{12}$C abundance ratio of 0.01. $^{13}$C is even more decisive for the $^{7}$/6 and Li/Be ratios. Taking all the ratios together, it is seen that with the conservative estimate, $^{13}$C/$^{12}$C $\sim$ 0.01,
each of the light element abundance ratios can be satisfactorily matched if one assumes an appropriate proton spectrum concentrated in the region between 10 and 25 MeV.

While this degree of agreement is encouraging, it is to be noted that the overall analysis is quite incomplete. As suggested above, further studies are required which will examine definite sites for the production process, specify plausible proton spectral shapes, and consider the effects of light element production by alpha particle reactions and the effects of destruction processes after the light elements are formed.


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

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

The abundance of $\alpha$ particles, in the cosmic ray flux (expressed in energy per nucleon) or as a target, is of the order of 10% that of protons, and therefore it might be expected that $\alpha$ particles would play relatively little role in the synthesis of the light elements. However, as projectiles they have very low reaction thresholds, again if expressed in MeV per nucleon, and for incident CNO nuclei of given energy the c.m. energy will be much greater for $^4$He than for $^1$H targets. Thus, if the incident spectra are rising rapidly at low energies, $\alpha$-particle reactions will be enhanced. The $\alpha$-particle reactions with lowest thresholds are those for the production of $^6$Li and $^{10}$B in interactions with $^{14}$N, with thresholds at 2.83 and 3.73 MeV per nucleon, respectively. It is presumed that $^{10}$B is produced primarily in the $(\alpha,2\alpha)$ reaction, with some contribution from $(\alpha,3\alpha)$. At the lowest incident energies $^6$Li is produced through the reaction $^{14}$N$(\alpha,^3$C)$^6$Li, but above the $^{14}$N$(\alpha,3\alpha)^6$Li threshold at 20.7 MeV, a major contribution is presumed to come from events proceeding through excited states of $^{10}$B which decay by $\alpha$-particle emission. We have measured the cross sections for $^6$Li and $^{10}$B production, summed over all reaction channels, using time-of-flight techniques to identify the reaction products of interest.

Measurements were made at incident $\alpha$-particle energies of 21, 23, 25, and 26 MeV using the tandem Van de Graaff accelerator and at 31.5, 34.4, and 42.1 MeV
using the cyclotron. The lower cyclotron energies were obtained by degrading the 42-MeV α-particle beam with beryllium foils. The basic experimental arrangement was the same for the Van de Graaff and cyclotron runs. In each case, time-of-flight particle identification was carried out using two independent solid state detector telescopes situated 10° apart and 64 cm from the target. All 6Li and heavier ions stopped in the first detector of the telescope; a second detector was used for anti-coincidence rejection of high energy α particles and lighter ions.

The particle energy was determined from an amplified linear signal from the front detector. The flight time was established by starting a time-to-amplitude-converter (TAC) with a fast signal from the front detector and stopping it with a signal from the accelerator. In the case of the Van de Graaff, the beam was chopped and bunched at low energies, and the stop signal came from the buncher oscillator. For the cyclotron the natural bunching of the beam was used, and the stop signal came from the cyclotron oscillator.

The energy signal and the TAC output for each telescope were fed to the input analog-to-digital converters of an on-line XDS-930 computer. Mass identification was accomplished within the computer, to develop a two-dimensional display of mass vs particle energy, in which particles of the same mass fall in a horizontal band. The basic data of the measurements were the number of counts at each point of this two-dimensional mass-energy array. Differential c.m. cross sections for the production of 6Li and 10B were extracted from the laboratory angular distributions, and total cross sections obtained by integration over the c.m. angular distributions. The conversion to the c.m. system provided points in the continuum distributions extending to very low c.m. energies, obviating the need for extrapolation to low energies. However, especially at low energies, the resulting angular distributions extended over only limited ranges, and extrapolation over the full angular range depended on the assumption, reasonably supported by the data, that the continuum distributions could be fitted with a sum of Legendre polynomials extending to \( P_2(\cos \theta) \).

Excitation functions resulting from this analysis are shown in Figs. 6.2-1 and 6.2-2. For the 6Li results, the yields for reactions to the 12C ground state, the 12C 4.43-MeV state and the continuum are plotted separately, together with the combined total yield. The continuum cross sections, for both the 6Li and 10B results, include both the true continuum and the superposed discrete states.

The most important consequence for light element production of high fluxes of low energy alpha particles is probably the production of Li from the reactions \( ^{4}\text{He}(\alpha,p)^{7}\text{Li} \) and \( ^{4}\text{He}(\alpha,d)^{8}\text{Li} \), with thresholds at alpha-particle energies of 34.7 MeV and 44.7 MeV, respectively. However, the present results show that at still lower energies there are sizable yields of 7Li and 11B from alpha particle reactions with \( ^{14}\text{N} \). Thus for particle spectra concentrated at very low energies, as might be the case for example for production in supernovae, 6Li and 10B production may occur either in alpha-particle reactions on \( ^{14}\text{N} \) or in proton reactions on \( ^{13}\text{C} \), while the more abundant isotopes, 7Li and 11B, can be copiously produced in proton reactions on \( ^{14}\text{N} \).

A fuller discussion of the experimental procedures and results for the present \( \alpha \) particle work and for related studies of proton reactions on \( ^{14}\text{N} \) has been submitted for publication.
Fig. 6.2-1. Cross sections for the production of \(^6\)Li in the \(\alpha\)-particle bombardment of \(^{14}\)N as a function of \(\alpha\)-particle energy. Separate plots are given for cross sections for the bound states of \(^{12}\)C, for the \(3\alpha\) continuum region, and for the sum. The curves through the data points are to guide the eye, and for the continuum and total cross sections are qualitatively speculative. Cross sections for the \(^{12}\)C ground state determined from the \(^{12}\)C\((^6\)Li,\(\alpha\))\(^{14}\)N measurements of Johnson and Waggoner (Ref. 4) are also shown.

Fig. 6.2-2. Total cross section for the production of \(^{10}\)B in the \(\alpha\)-particle bombardment of \(^{14}\)N as a function of \(\alpha\)-particle energy. The curve through the data points is to guide the eye.

1. See Sec. 6.1 of this report.
6.3 Electromagnetic De-excitation of Excited States in $^{12}C$

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

The branching ratios, $\Gamma_{\text{rad}}/\Gamma$, for the 7.65-MeV and 9.64-MeV states of $^{12}C$ have been studied experimentally, using a recoil coincidence method in which radiative transitions are recognized through a search for coincidences between inelastically scattered alpha particles and associated $^{12}C$ ions. The present report describes the final results of this study.

From further analysis of the experimental data for the 7.65-MeV state it is concluded that $\Gamma_{\text{rad}}/\Gamma = (4.20 \pm 0.22) \times 10^{-4}$, in essential agreement with the previously reported preliminary value of $(4.3 \pm 0.4) \times 10^{-4}$, and still in substantial disagreement with the earlier standard value of $(2.9 \pm 0.3) \times 10^{-4}$. The new value for the branching ratio corresponds to a radiative width for the 7.65-MeV state of $\Gamma_{\text{rad}} = \Gamma_{\gamma} + \Gamma_{\text{el}} = (3.9 \pm 1.2)$ meV. This result implies a higher rate for the triple-alpha process at given temperature and density than follows from the earlier values, and thus some increase in the ratio of the $^{12}C$ abundance to the $^{16}O$ abundance at the end of helium burning. A more complete description of the measurements has been published.

Although the triple-alpha process proceeds almost exclusively through the 7.65-MeV state at temperatures ($< 2 \times 10^{8}$ K) characteristic of helium burning in the ordinary sequence of stellar evolution, more highly excited states could conceivably play a role at the very high temperatures characteristic of explosive situations, such as supernovae and, possibly, big or little bangs. More specifically, the triple-alpha process rates for the 7.65-MeV state and the next higher state at 9.64 MeV become equal at $7 \times 10^{9}$ K, where the 9.64-MeV radiative width is taken to be 10 meV. As previously discussed, there is no experimental basis for this estimate of $\Gamma_{\text{rad}}$, and much higher values (up to ~1 eV) cannot be excluded on the basis of the systematics of isospin forbidden El transitions.

Our measurements for the 9.64-MeV state have given no evidence of coincidence events other than those attributable to background. The largest background contribution was from $\alpha - ^{12}C$ coincidences arising from the $^{12}C(\alpha,\alpha n)^{12}C$, reaction. The $^{12}C$ remained a troublesome target impurity in the $^{12}C$ targets, despite attempts to obtain highly enriched $^{12}C$ and to minimize buildup of natural carbon. Typically, the $^{13}C/^{12}C$ ratio in the targets was about 1/30 that of natural C.

Data used for the final analysis were taken in two different series of runs, with approximately equal numbers of counts in each. Results for the second series are displayed in Fig. 6.3-1. In the lower half of the figure the $\alpha'$ energy spectrum is displayed for those coincidence events for which the flight time difference between the two particles was consistent with $\alpha' - ^{12}C$ coincidences, and for which the energy in the $^{12}C$ detector was within a 0.7-MeV wide band expected to contain 90% of the $^{12}C$ group for the 9.64-MeV state. No clear peak can be seen in the $\alpha'$ spectrum. The position and shape of the expected $\alpha'$ peak is also shown, as obtained in a calibration run in which the energy threshold of the $^{12}C$ detector was lowered to accept single alpha particles from the breakup of the excited $^{12}C$. 

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A large fraction of the observed counts are attributable to the $^{13}$C impurity, and a spectrum for the expected $^{13}$C impurity events is plotted in the figure. The shape of the spectrum was obtained in a run with an isotopically enriched $^{13}$C target, and the absolute normalization was established by comparing, for the $^{13}$C run and the data run, the number of counts in a strong coincidence group arising from the $^{13}$C$(\alpha,\alpha'n)^{12}$C reaction proceeding through the 7.55-MeV state of $^{13}$C.

The difference between the observed counts and the counts attributable to the $^{13}$C impurity is plotted in the upper half of Fig. 6.3-1. The net counts in the region which contains 90% of the 9.64-MeV $\alpha'$ peak is $5.9 \pm 5.2$, where the uncertainty is the statistical standard deviation. This number of coincidence counts is not appreciably larger than the number of analogous counts in neighboring regions of the $\alpha'$ - $^{12}$C two-dimensional energy spectrum and thus may correspond in large part to an unexplained background. Runs with targets rich in N and O showed no contribution to the region of interest from N or O impurities, although there was a small contribution to neighboring regions. The net number of counts from the first series of runs was $0.3 \pm 5.4$.

Taken together with the measured number of inelastic alpha particles and the efficiency for $^{12}$C detection, these results lead to upper limits on the branching ratio of $4.1 \times 10^{-7}$ at a confidence level corresponding roughly to one standard deviation, and to $8.2 \times 10^{-7}$ at a 95% confidence level. The higher of these two limits implies an upper limit on the radiative width, $\Gamma_{\text{rad}} < 28$ meV. The previously cited estimate, $\Gamma_{\text{rad}} = 10$ meV, is within this limit. More significantly, much larger values of $\Gamma_{\text{rad}}$, which would have been consistent with the transition systematics, are excluded by the present experimental results.

7. WEAK INTERACTIONS

7.1 Introduction

The study of parity-violating (PV) nucleon-nucleon forces provides a unique opportunity to observe the weak hadronic current \( J_\mu \) interacting with itself.\(^1\)\(^2\) This current has two components and is conventionally expressed as \( J_\mu = \cos \theta \, J_0 + \sin \theta \, J_1 \) where \( \theta \approx 15^\circ \) is the Cabibbo angle, \( J_0 \) is the strangeness conserving (\( \Delta S = 0, \Delta T = 1 \)) current responsible for nuclear \( \beta \) decay and \( J_1 \) is the strangeness changing (\( \Delta S = 1, \Delta T = 1/2 \)) current responsible for the decay \( \pi^+ \rightarrow \pi^0 + e^+ + \nu \). The PV nucleon-nucleon force is described by an interaction \( \cos \theta \, J_0 J_0^\dagger + \sin \theta \, J_1 J_1^\dagger \). The term \( J_0 J_0^\dagger \) transforms as a mixture of isoscalar and isotensor quantities, while the term \( J_1 J_1^\dagger \) transforms as an isovector. Thus by probing the isospin character of the PV interaction one can separate the contributions from the currents \( J_0 \) and \( J_1 \). At present most experimental evidence for parity admixtures in nuclei comes from circular polarization measurements in heavy nuclei (for a review of experiment and theory see Ref. 3). In these nuclei the complexity of the nuclear physics tends to obscure the properties of the basic PV interaction. It is clearly of great interest to study parity mixing in light nuclei where the nuclear physics is relatively tractable and where one can elucidate the isospin structure of the PV forces. Prior to this work there existed only two positive measurements of PV transitions in light nuclei -- a circular polarization measurement of the \( \gamma \)-rays from thermal neutron capture by hydrogen\(^4\) -- and a measurement of the PV \( \alpha \)-decay of the 8.8 MeV \( 2^+ \) level of \( ^{16}O \).\(^5\) Both of these measurements are sensitive only to the isoscalar PV interaction.\(^6\) We have undertaken a program to observe PV effects in light nuclei which are sensitive to the isovector interaction. This work is a continuation of the efforts described in last year's Annual Report.

In Sec. 7.2 an experiment that measures parity-mixing in \( ^{19}F \) is described. In Sec. 7.3 a calculation of the analyzing efficiency of \( \gamma \)-ray circular polarimeters is described. This is needed for the analysis of the \( ^{19}F \) experiment. In Sec. 7.4 a novel method of attempting to measure the \( \Delta T = 1 \) weak force is examined.

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7.2 Parity Mixing of the Ground State Doublet in $^{19}F$

E.C. Adelberger, M.D. Cooper, H.E. Swanson, J.W. Tape, and T.A. Trainor

Nuclear Physics

A level diagram of the low-lying $J = 1/2$ levels of $^{19}F$ is shown in Fig. 7.2-1. As was first pointed out by Maqueda\(^1\), the ground and 110 keV states provide an unusually clean system in which to study parity violation. We can treat the PV interaction as a perturbation, and have a situation which should be well approximated by two-state mixing since the energy denominator of the next-nearest $J = 1/2$ state is 50 times greater than the 0.11 MeV splitting of the ground-state doublet.

$$
|\text{g.s.}\rangle = |\rightarrow\rangle - \varepsilon |\leftarrow\rangle
$$

$$
|110\rangle = |\leftarrow\rangle + \varepsilon |\rightarrow\rangle
$$

$$
\varepsilon = \frac{\langle -|H_{\text{PV}}|+\rangle}{110 \text{ keV}}
$$

The EM matrix element is then

$$
\langle \text{g.s.} | E1+M1 | 110 \rangle = \langle \rightarrow | E1 | \leftarrow \rangle + \varepsilon [\langle \rightarrow | M1 | + \rangle - \langle \leftarrow | M1 | - \rangle] + \theta(\varepsilon^2).
$$

In this case the PV transition is M1 and the EM matrix element can be calculated essentially exactly once $\varepsilon$ is known, since it is given by the magnetic moments of the ground and 110 keV levels. We find $\mu_{\text{g.s.}} = 2.629\ \mu_N$ and assume $\mu_{110} = \mu_{15N} = -0.283\ \mu_N$. The calculated transition is unusually fast, 1.58 $e^2$ W.u. while the parity allowed E1 transition is quite retarded ($\approx 10^{-3}$ W.u.) enhancing our sensitivity to the parity violation. The great speed of the M1 transition provides additional support for the two-state approximation as applied to the parity admixture since it is very unlikely that any other possible admixed levels will carry much greater M1 strength.

The PV M1/E1 mixing ratio can be determined by measuring the anisotropy $(1 + P_\rho \cos \theta)$ of 110 keV deexcitation gamma rays from polarized $^{19}F$ nuclei. In the expression for the anisotropy $P_\rho$ is the average polarization of the $^{19}F$ ions, $\cos \theta = \sigma_T \cdot \hat{\rho}$, and $\delta$ is proportional to $\varepsilon$ and involves the magnetic moments and the E1 lifetime. There are three calculations of the PV coefficient $\delta$. Using Michel's PV single-body potential Maqueda\(^1\) predicts $|\delta| = 4.3 \times 10^{-4}$. Gari et al.\(^2\) have performed calculations using a two-body $\rho$-exchange ($\Delta T = 0$) potential. With the Reid soft-core N-N potential without correlations they predict $|\delta| = 2.0 \times 10^{-4}$. With correlated wave functions they predict $|\delta| = (0.5 - 0.9) \times 10^{-4}$ depending on the type of correlations assumed. Calculations of McKellar and Box\(^3\) indicate that the $\rho$ ($\Delta T = 0$) and $\pi$ ($\Delta T = 1$) exchange contributions are $|\delta| = 3 \times 10^{-4}$ and

<table>
<thead>
<tr>
<th>Level</th>
<th>$J^p$</th>
<th>$E_\gamma$ (keV)</th>
</tr>
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<tbody>
<tr>
<td>5943</td>
<td>$1/2^+$</td>
<td></td>
</tr>
<tr>
<td>5630</td>
<td>$1/2,3/2^-$</td>
<td></td>
</tr>
<tr>
<td>5340</td>
<td>1/2</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7.2-1. Level diagram of the low-lying $T=1/2$ levels in $^{19}F$. 

\[ |\delta| = 0.5 \times 10^{-4} \] respectively, without correlations. With correlations the \( \rho \) contribution is reduced to \( 0.5 \times 10^{-4} \) while the \( \pi \) contribution is essentially unchanged. In principle one should be able to predict the sign as well as the magnitude of \( \delta \). However to get the sign correct one must know the sign of the El matrix element and one cannot trust a calculation to give the correct sign for such a retarded transition.

Experimental Design

The experiment is designed to detect an asymmetry \( \delta \) of roughly \( 10^{-5} \). The \( ^{19}_p \)'s are polarized by producing them in the \( ^{22}\text{Ne}(p,\alpha) \) reaction using a polarized proton beam at an energy of 4.93 MeV. The physical layout of the experiment is shown in Fig. 7.2-2. The beam is transversely polarized (right or left) and passes through a thin-walled (0.25 mm Al wall thickness) gas cell with \( 2 \times 10^{-4} \) cm thick Ni entrance and exit foils. The cell is viewed by two thin-window planar Ge(Li) detectors. The detectors have a nominal area of 10 cm\(^2\) and a nominal thickness of 0.7 cm. Under our high counting-rate conditions they give a resolution for 122 keV gamma rays of 1 keV. The cell is designed so that both counters see the entire interaction volume. The beam is collimated by two .24 cm diameter carbon collimators located 7.6 and 17.8 cm upstream from the entrance foil. A \(^4\text{He} \) proton polarimeter is located in a separate scattering chamber upstream from the \(^{22}\text{Ne} \) gas cell. The polarimeter can be swung in and out of the beam and is used to monitor periodically the beam polarization. The outputs from the Ge(Li) detectors are digitized in two fast (7 usec/event) analyzers (Nuclear Data ND2400 with 100 MHz ADC's). The polarization state of the beam is switched repetitively (usually right-left) and the ADC output is routed into two halves of the ND2400 memories according to the polarization state. The block diagram of the experiment control electronics is shown in Fig. 7.2-3. The data collection is completely automatic. The experiment controller, counting room scalers and the ND2400 analyzers are controlled by the on-line computer. The computer starts the analyzers at the beginning of a spin-switching cycle. Many cycles later, after a predetermined bombarding charge has accumulated, counting is stopped at the end of the next complete cycle. Contents of the analyzers and scalers are transferred to the computer memory, the computer writes this information on magnetic tape, clears and then restarts the analyzers and scalers at the beginning of the next spin cycle. Each of these sequences, a so-called "dump", contains \( \approx 10^7 \) counts in the 110 keV peak. The computer prints out peak areas and various counting rate ratios at the end of each "dump". By checking the fluctuations on the counting rates from "dump" to "dump" we are able to see if the deviations are consistent with counting statistics or if other sources of "noise" are present.
Polarizing the $^{19}$F⁺⁺'s

The $^{22}$Ne(p,α)$^{19}$F⁺⁺ reaction has a spin structure $0^+ + 1/2^+ \rightarrow 0^+ + 1/2^-$. Angular-momentum and parity conservation restrict the reaction matrix to the form $(a P_z)$ where the z axis lies along the beam direction and the y axis is normal to the reaction plane. Thus, the polarization vector of the $^{19}$F⁺ ions $\vec{P}_F$ is related to the polarization vector of the beam $\vec{P}_P$ by

$$\sigma = |a|^2 + |b|^2$$

$$\sigma_{P_x} = -|a|^2 P_x$$

$$\sigma_{P_y} = -|a|^2 P_y$$

$$\sigma_{P_z} = (|a|^2 - |b|^2) P_z$$

and the analyzing power of the reaction is given by

$$\sigma A = 2\text{Im}(ab^*)$$

Thus we see that large transverse polarization transfers are expected. For instance, for s-wave α's b = 0 and $P_y = -P_x$. This relation holds even when one averages over all α angles and employs a thick target. An excitation function for 110 keV radiation from the $^{22}$Ne(p,α) reaction is shown in Fig. 7.2-4.
Fig. 7.2-4. Cross sectional view of the transmission-type Compton polarimeter. This device is used to determine the net polarization of the $^{19}$F* nuclei by measuring the circular polarization of the 110 keV deexcitation radiation.

A prominent enhancement is seen at a bombarding energy of 4.7 MeV, corresponding to an α-particle cm energy of only 2.0 MeV. The target thickness selected for the parity measurements is indicated in the figure and encompasses this intense maximum in the yield. The polarization transferred to the $^{19}$F* ions must be retained for a time $\tau$; the radiative lifetime of the 110 keV level which is $\sim$1ns. This is achieved by picking a gas pressure low enough so that the $^{19}$F* ions decay before coming to rest. In this fashion the $^{19}$F* nuclei see randomly directed, hyperfine fields and experience very little depolarization.

Measuring the $^{19}$F* Polarization

We are interested in the net $^{19}$F* polarization averaged over the radiative lifetime of the 110 keV state. This cannot be obtained from measurements of the analyzing power for the reaction. For instance, for s-wave α's $A = 0$, but the polarization transfer is -1. The net $^{19}$F* polarization can be obtained from a measurement of the circular polarization of the deexcitation radiation. For the case of a $j = 1/2 + j = 1/2$ transition the circular polarization of the gamma rays is numerically equal to the linear polarization of the $^{19}$F* nuclei. The circular polarization was detected using a symmetrical transmission-type Compton polarimeter (see Fig. 7.2-4). The proton spin direction was held constant while the magnetic field direction was reversed once each second. The counter outputs were routed according to the field direction. In order to remove effects of
small beam position changes due to asymmetrical stray magnetic fields, data was taken with the proton spin first right and then left. Also, data was taken with the magnet in its normal position and in a position rotated through 180° about the beam axis. The beam position changes should be correlated only with the magnetic field direction, whereas circular polarization effects are correlated with the product of proton spin and magnetic field orientations. Therefore, rotating the magnet by 180° should not change the circular polarization effect but will reverse fringing fields due to magnet asymmetries. The gamma circular polarization was deduced from the ratio \( A_{\gamma} = \frac{R^+}{L^+} \frac{L^-}{R^-} = 1 + 4\eta P^F \) where \( R^+ \) and \( L^+ \) are the counting rates in the right and left counters with the iron magnetized in the +, - directions, and \( \eta \) is the analyzing efficiency of the circular polarimeter. The data are shown in Fig. 7.2-5. From these data and the calculated \( \eta \) discussed in Sec. 7.3, we infer a net \( 19 \) polarization transfer (averaged over the 0.85 ns lifetime) of \( T = -(0.73 \pm 0.15) \).

Measuring the PV Asymmetry Coefficient

The asymmetry \( \delta \) is measured by removing the polarimeter magnet and placing the counters 5 cm to the right and left of the beam. The proton spin state is switched with a fixed period selectable from 0.202 sec to 1.002 sec. The anisotropy is obtained from the ratio \( A_{PV} = \frac{R^+}{L^+} \frac{L^-}{R^-} = 1 + 46P^F \). The ratio \( A_{\gamma} \) is defined similarly to \( A_{\gamma} \) except that now \( \pm \) refer to the directions of the proton spin. In any experiment which purports to measure very small quantities one must carefully consider sources of spurious effects. In our experiment we must ask "what else do we do when we flip the spin?" We are aware of the following possible sources of instrumental asymmetries:

a) correlations of beam position and intensity with spin state.

b) spin-orbit forces plus a misalignment of the proton spin.

c) correlations between beam angle and spin state.

Let us consider these "fake" asymmetries in turn. Suppose that whenever the spin is flipped the centroid of the beam is also slightly displaced. A displacement of \( 5 \times 10^{-5} \) cm would be sufficient to produce a "fake parity effect" of \( 1 \times 10^{-5} \). Clearly one cannot trust the ion source to this level of precision. This instrumental asymmetry is removed by the following strategy. We choose a beam energy such that in addition to 110 keV radiation from \( ^{22}\text{Ne}(p,\alpha) \) we also produce 74 keV radiation from the \( ^{22}\text{Ne}(p,\gamma) \) reaction. The 74 keV radiation comes from the decay of a \( J = 0 \) level and hence is isotropic. By taking the ratio of 110 keV to 74 keV \( \gamma \)-rays in each spectrum we correct very accurately for correlated beam position shifts, dead time effects, etc. From the apparent asymmetry of the 74 keV \( \gamma \)-rays measured during the most recent runs we can conclude that when the spin direction is reversed, the beam moves only \( 4.4 \times 10^{-4} \) cm, which is quite impressive.

The spin-orbit force produces no asymmetries if the left-right axis between the two counters lies along the proton polarization axis. If the spin axis is azimuthally misaligned with respect to the axis between the counters the L·S force can produce \( ^{19}\text{Ne} \) ions which preferentially recoil toward one counter or the other. This would create an artificially high counting rate which would follow
the proton spin direction and mimic a parity violation. [Of course if the 
outgoing \( \alpha \)'s are purely s-wave there is no problem.] We have reduced this 
problem to a negligible level by align-
ing our counters to an accuracy of 0.3°. 
The L-S effects were measured by rotat-
ing the proton spin 90° so that it 
pointed up-down. At this angle the 
parity-violating asymmetry vanishes, 
but the apparent asymmetry \( A' \) due to 
L-S forces is maximum. From this meas-
urement we know that the counter axis 
must lie along the spin axis to an 
azimuthal accuracy of 0.1° if the in-
strumental asymmetry is to be \( 1 \times 10^{-5} \). 
The alignment is performed in two 
 stages. First the gas cell is replaced 
by a \( ^{57} \text{Co} \) source in a precision jig. 
The source is moved vertically between 
the counters. The counter positions 
are adjusted so the maxima in the count-
ing rates for the two detectors occur 
when the source is at the center of the 
cell. The proton spin alignment is 
checked by rotating the helium polar-
imeter by 90° so that the two counter 
apertures lie on an accurate horizontal 
axis. In this configuration there 
should be no asymmetry in the counting 
 rates in the polarimeter detectors if 
the spin were truly horizontal. This 
is checked by using the spin-flip scle-
noid to rotate the proton spin through 
small angles about the nominal horiz-
tonal direction in order to find the angle 
at which the asymmetry vanishes. From 
such measurements we know that the spin 
is horizontal to an accuracy of 0.3 ± 
0.3°. A more accurate measurement of 
this angle is in progress.

The most subtle instrumental asymmetry arises from the difference in the 
excitation functions of 110 and 74 keV \( \gamma \) rays (see Fig. 7.2-6). As a conse-
quence the centroid of the 74 keV \( \gamma \)-ray source is 1.2 cm upstream from the cen-
troid of the 110 keV \( \gamma \)-rays. If the angle of the beam passing through target 
is slightly different in the two spin states a false asymmetry will result. An 
gle change of 0.0023 deg is sufficient to cause a false asymmetry of \( 1 \times 10^{-5} \). 
Such an angle is small enough that one cannot a priori rule this out as a source 
of error. However, crude arguments based on beam optics in the ion source lead 
us to expect that angle shifts of this magnitude would have to be accompanied
by position shifts at the gas cell which are much larger than we observe. Furthermore, we expect that beam-angle changes should be correlated with the direction of those magnetic fields in the ion source which are repetitively switched. We attempt to cancel such correlations by using two different methods of producing a particular spin orientation at the target. These correspond to opposite directions of the switching magnetic fields. We run for equal charges in the two configurations and combine the results. The parity violating asymmetry is the same in both configurations while spurious effects related to the sign of the switching field have opposite signs and vanish in the combination. The source produces $H^+$ ions polarized along (or against) the beam axis. The longitudinal spin is then precessed transversely by crossed E and B fields in the "Wien filter". We have chosen a beam line which gives a net proton spin precession in the beam transport system of $-4.15^\circ$ so that the precession required in the Wien filter is $90^\circ$. Thus, with opposite and essentially equal Wien fields we can precess the spin clockwise or counter clockwise. These two precession directions correspond to the two different methods of producing a particular spin orientation.

We have run with three different switching-field configurations in the ion source in order to develop an optimum combination of large beam polarization and small beam modulation. These configurations are discussed further in Sec. 9.1. We have at present completed four experimental runs. The results are shown in Table 7.2-1. Runs 1 and 2 were done with the configuration depicted at the top of Fig. 9.1-1, where the nominal polarization switches from 100% right to 100% left. Although this configuration gave a maximum polarization difference it caused a considerable modulation of the beam. Run 3 was performed with the configuration shown in the middle of Fig. 9.1-1. Here the beam was switched from polarized to unpolarized which gave much reduced modulation. Run 4 was done with the scheme shown at the bottom of Fig. 9.1-1. Here the nominal polarization went from 50% right to 50% left and the modulation was very small. We feel that Run 4 represents the most reliable of the four runs because of the small size of the observed intensity and position modulations. The results of this run are clearly inconsistent with those of run 1. We cannot account for this at present; clearly more data is needed. The asymmetry, $\delta$, measured in run 4 is only 1.5 standard deviations away from zero. We have decided to temporarily forego improving the statistical error until we understand the question of possible angle modulations on the beam. Current efforts are devoted to a direct measurement of the angle modulations using Rutherford scattering from a thin gold foil. When we are satisfied that any angle modulations are insignificant or else reproducible, we will devote running time to increasing the statistical accuracy of our data.

<table>
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<th>Run</th>
<th>T6</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>$(4.8 \pm 1.2) \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>$(2.8 \pm 1.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>$(1.8 \pm 2.3) \times 10^{-4}$</td>
</tr>
<tr>
<td>4</td>
<td>$(1.2 \pm 0.83) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 7.2-1. Measurements of T6, the Product of the Polarization Transfer Times the Parity Violating Asymmetry Coefficient.
Analyzing Power of a Transmission Polarimeter for Circularly Polarized Gamma Rays

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

The circular polarization of the 110 keV gamma rays from the decay of the $^{19}F$ 1/2$^-$ state was determined using a transmission type polarimeter. The measurement of the circular polarization is performed by allowing the gamma rays to propagate through a slab of iron which is alternately magnetized such that the direction of the magnetization has a component which is parallel and then anti-parallel to the direction of propagation of the gamma rays. A term in the Compton scattering cross section which depends on the magnitudes of the electron polarization in the iron, the circular polarization of the gamma ray, and the angle between the electron polarization vector and the gamma ray direction, leads to an asymmetry in the counting rate depending on the direction of the field. The measurement of this asymmetry then can be used to deduce the magnitude of the circular polarization if the analyzing efficiency of the polarimeter is known.

The analyzing power of the polarimeter can be determined by calculating the transmission of the gamma rays for an ideal case in which the gamma rays and the electrons in the iron both have 100% polarization. The theoretical asymmetry thus obtained can be scaled by the known electron polarization (8%) and a comparison of this calculated asymmetry with the measured data yields the magnitude of the actual polarization of the gamma rays.

The geometry of the problem is shown in Fig. 7.2-4. The 110 keV gamma rays of interest in this problem can interact in the iron absorber by the photo effect, coherent (Rayleigh), and incoherent (Compton) scattering. Standard Monte Carlo type techniques were used to determine the intensity of gamma rays seen by the detector. The trajectory of a gamma ray was calculated starting from a random point on the line source in the gas cell and followed through an interaction in the iron and finally detection (or not) in the Ge(Li) counter.

The excellent energy resolution of the detectors (< 1 keV FWHM at 122 keV) simplified the calculation considerably. For example, multiple scattering can be treated as absorption since the probability of two scatterings which change the gamma ray energy by less than say 2 keV is small. Similarly the Compton differential cross section used to determine the (random) scattering angle need be calculated only over a limited angle region and the spin dependent part, which is small at small angles, can be neglected. The spin dependence of the transmission then enters only through the integrated cross section which is used to determine the interaction probability in the iron, the probability of Compton scattering into an angle less than the energy resolution, and in the multiple
scattering correction.

The differential cross section for coherent scattering is not well known and no simple expression approximating it seems to exist. It is known to be forward peaked and in the initial calculations it was approximated by a uniform scattering probability up to a variable cutoff angle. In the future a form derived from a paper by Brenner, Brown and Woodward⁴ will be used. In any case the total cross section is small compared to the other processes and thus the corrections should be small. Any spin dependence of the coherent scattering has been ignored as the scattering is mainly from K shell electrons which have no net polarization.²

The program written for the Laboratory SDS 930 computer is currently being tested by comparing the calculated transmission with experimental values for a 110 keV line source and a 122 keV point source. Preliminary results indicate an analyzing power of \(- (2.3 \pm 0.2) \times 10^{-3}\) which is consistent with estimates based on analyzing powers reported in the literature for other transmission polarimeters.³


7.4 On the Feasibility of Directly Measuring the $\Delta T = 1$ Parity Violating Force

E.G. Adelberger and J.E. Bussoletti

A measurement of the $\Delta T = 1$ parity violating (PV) force would be of very great interest.¹,² According to present ideas concerning the nature of weak interactions, it comes from the interaction of two strangeness changing hadronic currents. However no experiments have been reported which probe this force specifically. Measurements in deuterons³ and $^{16}$O⁴ are sensitive only to the $\Delta T = 0$ parity-violating force. The $^{19}$F parity mixing experiment (see Sec. 7.2 of this report) is sensitive to both $\Delta T = 0$ and $\Delta T = 1$ forces but, by itself, cannot separate the two contributions. The same is true for parity violating effects observed in heavier nuclei.

Experiments which are sensitive to only the $\Delta T = 1$ force have been suggested in $^{18}$F and $^{10}$B but they are extremely difficult. For example in $^{18}$F a $J^P; T = 0^+; 1$ state occurs at an excitation of 1.04 MeV while a $0^+; 0$ state is found at 1.08 MeV. The 1.08 MeV state has a lifetime ~$10^4$ times longer than the 1.04 MeV state, which enhances parity violating effects in the gamma decay of the 1.08 MeV state. One can presumably treat the parity violation as a two state mixing problem between the $0^+; 1$ and $0^+; 0$ states; thus PV effects arise only from the $\Delta T = 1$ force. Only two ways of detecting a PV effect in these states have
been suggested. One PV effect would be the presence of an azimuthal variation in the cross section for the $^{20}$Ne($d,α)^{18}$F(1.04)O$^+;I$ reaction. The reaction is isospin forbidden; the effect of a small component of the $0^+;0$ state mixed into the $0^+;I$ state would be enhanced. However, the cross section for the reaction $^{20}$Ne($d,α)^{18}$F(1.08)O$^−;0$ is quite small. Also there would be considerable difficulty in resolving the $0^+;0^−$ states from each other and from the $3^+;0$ and $5^+;0$ states at 0.94 and 1.12 MeV. A measurement of the circular polarization of the decay gammas from the $^{18}$F(1.08)O$^−;0$ state also measures a parity violating effect. However the 1.08 MeV gamma is expected to have a circular polarization of $\approx 10^{-5}$. The measurement at such a small circular polarization is extremely difficult since the gamma ray would have to be produced by a "noisy" accelerator beam rather than by a "quiet" radioactive source; essentially all previous measurements of circular polarizations of such small size have used a radioactive source.

We have nonetheless made one attempt to measure the yield of 1.08 MeV gamma rays in the $^{18}$O($h,p)^{18}$F(1.08) reaction at a bombarding energy at 5.0 MeV. We found the yield to be impractically low and the background excessively high.

We have considered a novel method of separating the $ΔT = 1$ weak force effects from the $ΔT = 0$ effects by comparing analog parity violating transitions in mirror $T = 1/2$ nuclei. In particular we have investigated the possibility of comparing the $J_π \cdot H_π^PV$ anisotropies of the gamma decays of the lower $1/2^−$ levels in $^{19}$Ne and $^{19}$F to their $1/2^+$ ground states.

Consider first the ideal case of a $T = 1/2$ multiplet of $1/2^−$ and $1/2^+$ states; let the energy separation of the $1/2^−$ and $1/2^+$ states be $δ$. The parity violating anisotropy $δ$ is given by

$$\delta = \frac{\langle 1/2^+ | H_π^PV | 1/2^− \rangle}{\Delta} \frac{⟨M_{1}⟩}{⟨E_{1}⟩}$$

where $⟨E_{1}⟩$ is the (allowed) $E1$ matrix element between the $1/2^+$ and $1/2^−$ states and $⟨M_{1}⟩$ is the irregular $M1$ matrix element.

If the $M1$ is purely an isovector $M1$, the Wigner-Eckart theorem tells us that the ratio $⟨M_{1}⟩/⟨E_{1}⟩$ doesn't change sign for the two different members of the $T = 1/2$ multiplet. However,

$$H_π^PV = H_π^{ΔT=0} + H_π^{ΔT=1}$$

Although the $ΔT = 0$ contributions have the same sign for $g_z = ±1/2$, the $ΔT = 1$ contributions have opposite signs in the two cases. If we denote the isospin reduced matrix elements

$$\langle 1/2^+ | H_π^{ΔT=0} | 1/2^− \rangle by ε^0, and \langle 1/2^+ | H_π^{ΔT=1} | 1/2^− \rangle by ε^1,$$

the ratio of the two asymmetries is

61
\[ A(\tau_z = +1/2) = \frac{1 + P_+ ((\varepsilon^0 + \varepsilon^1) / \Delta)(\langle M_L \rangle / \langle E1 \rangle)}{1 + P_- ((\varepsilon^0 - \varepsilon^1) / \Delta)(\langle M_L \rangle / \langle E1 \rangle)} \]

\[ A(\tau_z = -1/2) = 1 + \langle M_L \rangle / \Delta \langle E1 \rangle \left[ (P_+ - P_-) \varepsilon^0 + (P_+ + P_-) \varepsilon^1 \right]. \]

If we can polarize each state equally, we have simply

\[ \frac{A(\tau_z = +1/2)}{A(\tau_z = -1/2)} = 1 + \frac{\langle M_L \rangle}{\Delta \langle E1 \rangle} \varepsilon^1 \]

In the realistic case Nature is not so kind. We find that

\[ \langle M_L \rangle_{T=1} = 2.76 \text{ nm} \]
\[ |\langle E1 \rangle_{\tau_z = +1/2}|^2 = 1.21 \times 10^{-3} \text{ W.u.} \]
\[ \langle M_L \rangle_{T=0} = 0.153 \text{ nm} \]
\[ |\langle E1 \rangle_{\tau_z = -1/2}|^2 = 1.07 \times 10^{-3} \text{ W.u.} \]

and most importantly,

\[ \Delta(\tau_z = +1/2) = 0.110 \text{ MeV} \quad \Delta(\tau_z = -1/2) = 0.275 \text{ MeV}. \]

If we include these effects we find that if the polarizations are equal, the \( \Delta T = 1 \) force is only enhanced relative to the \( \Delta T = 0 \) force by a factor of 3. This is not a sufficient enhancement to allow a good measurement of the \( \Delta T = 1 \) force if theoretical estimates (which give \( H_{\Delta T=1}/H_{\Delta T=0} \sim \tan^2 \theta_C \sim 1/20 \), where \( \theta_C \) is the Cabibbo angle) are correct. In spite of this it would be interesting to have some experimental evidence on the size of the \( \Delta T = 1 \) force, since it is not obvious that the theory is correct.

We consider an experiment to compare the anisotropies from polarized \( ^{19}F \) and \( ^{19}Ne \) where we populate the \( 1/2^- \) levels in the \( ^{19}F(p,p') \) and \( ^{19}F(p,n') \) reactions. The experiment would be similar to the \( ^{19}F \) parity mixing experiment reported above, except that instead of measuring the \( ^{19}F \) anisotropy with respect to an isotropic \( ^{22}Na \) decay we would measure the \( ^{19}F \) anisotropy with respect to the corresponding \( ^{19}Ne \) anisotropy.

We have measured the yield at 275 keV gammas from the reaction \( ^{19}F(p,n)^{19}Ne \) and compared the yield to that of 110 keV gammas from \( ^{19}F(p,p') \) in the energy range \( 5.0 \text{ MeV} \leq E_p \leq 9.5 \text{ MeV} \). The target was a 1.7 mg/cm\(^2\) foil of polyvinyl fluoride (PVF): \( ^3\text{C}_6\text{H}_{12}\text{F}_2 \). The gamma yield excitation function is shown in Fig. 7.4-1. The yield of the 275 keV gammas is disappointingly low; at best it is 1/20 of the yield of the 110 keV gammas. The yield is probably too low to allow us to use the \( ^{19}F(p,n) \) reaction to populate the \( ^{19}Ne \) state for a parity violation measurement.
Fig. 7.4-1. Excitation function for $^{19}\text{F} + p$ comparing total cross sections for the $^{19}\text{F}(p,p')^{19}\text{F}(0.110)$ and $^{19}\text{F}(p,n)^{19}\text{Ne}(0.275)$ reactions. For a feasible parity-violation experiment sensitive to the $\Delta T = 1$ force a high yield of these two analog $1/2^- \rightarrow 1/2^+$ transitions is required.

8. SCATTERING AND REACTIONS

8.1 Phenomenological and Microscopic Analysis of Elastic Scattering of a-Particles

J.S. Blair and W.Q. Summer

During the past few years extensive measurements have been made of the cross sections for the elastic scattering of 42 MeV alpha particles from a variety of isotopes. These have carried forward the program initiated by Fernandez and Blair and, as in that work, have focused on the small differences in the angular distributions of neighboring isotopes. Considerable care has been taken to measure accurately the locations of diffraction minima.

These data have now been subjected to analyses at two levels of sophistication. First, the angular distributions have been fitted to the predictions of a standard four parameter optical model; as has been often found before, the only quantities well pinned down in these analyses are the values of the real potential in the far tail where the magnitude of the potential is of the order of 2 to 3 MeV or less.

Second, nuclear densities have been related to the derived phenomenological potentials in the tail through a simple folding model. The effective alpha-nucleon interaction is calibrated by requiring that it give the derived phenomenological potential when folded with plausibly determined nuclear densities for \(^{40}\)Ca. In this work we have adopted for \(^{40}\)Ca the matter density generated by Negele's Hartree-Fock calculation; the corresponding proton distributions provide a good fit to elastic electron scattering. Using either a Gaussian or a Woods-Saxon effective alpha-nucleon interaction, we have then worked backward to derive nuclear densities for the other nuclei studied. We find that with this procedure the densities are determined reliably only in a region where the density is about 1/20 or 1/30 the central nuclear density. Further, on adopting proton densities extracted from analyses of the elastic scattering of high energy electrons, we can determine neutron densities in this same region.

As samples of our results, we list in Table 8.1-1 the radii at which the matter density equals 0.005 nucleons/F\(^3\) for a series of the nuclei studied by us. \(^{1}\)

Some of the trends which emerge from this work are: (1) Through the Ca and Ti isotopes, the matter densities in the far tail mirror what was already observed for the phenomenological optical potentials, namely, their expansion with A is at a lower rate than is typical for the periodic table as a whole. (2) On the other hand, the densities of Ni and Zn isotopes increase more rapidly than is typical. (3) The radii for the heavier Mo isotopes increase rather little, a behavior suggestive of the Ca isotopes.

Because of uncertainties in the proton distributions, neutron densities are much less reliably extracted than are matter densities. Nonetheless, we do claim: (4) There is a tendency for the neutrons to stick our farther than the protons. This tendency becomes more marked at the heavy end of an isotope string. (5) The derived neutron densities for the N = 28 isotopes appear
remarkably similar; our analysis indicates that the radii at which the neutron density equals 0.003 neutrons/F³, \( r = 5.60 \) F, do not differ by more than 0.02 F.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Radius (in F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40Ca</td>
<td>5.38</td>
</tr>
<tr>
<td>48Ca</td>
<td>5.54</td>
</tr>
<tr>
<td>62Ni</td>
<td>5.97</td>
</tr>
<tr>
<td>64Ni</td>
<td>6.05</td>
</tr>
<tr>
<td>63Cu</td>
<td>6.01</td>
</tr>
<tr>
<td>65Cu</td>
<td>6.07</td>
</tr>
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<td>64Zn</td>
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<td>68Zn</td>
<td>6.19</td>
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<td>92Mo</td>
<td>6.66</td>
</tr>
<tr>
<td>118Sn</td>
<td>7.19</td>
</tr>
<tr>
<td>208Pb</td>
<td>8.47</td>
</tr>
</tbody>
</table>


8.2 Highly Inelastic Deuteron Scattering at 45 MeV

I. Halpern, D. Hendrie, H. Wieman, and M.S. Zisman

The mechanisms for inelastic scatterings in which large amounts of energy are transferred are still not fully understood. Measurements of \((p,p')\)\(^1\), \((a,a')\)\(^2\), and \((^3\text{He},^3\text{He}')\)\(^2\) for 40-100 MeV projectiles have shown that there is a large direct inelastic cross section that accounts for 10% or more of the total reaction cross section. In the case of the \((a,a')\) reaction, a portion of the observed \(a'\) spectrum has been explained in terms of the \((a,^3\text{He})\)\(^3\) reaction and considerable effort has been directed toward interpreting other portions of the \(a'\) spectrum in terms.
of collective multipole resonances.\textsuperscript{4,5}

In pursuing the subject of highly inelastic scattering we have used 45 MeV deuterons from the 88 inch Berkeley cyclotron to measure (d,d') spectra at a number of angles for targets having A values from 27 to 208.

The data were taken using two particle ID telescopes adjusted to different energy intervals in order to cover the full energy range. This method has the difficulty that one must join the two separately measured spectra. It was however superior to using a single three detector telescope since such a telescope distorts the spectrum in the region where particles are just starting to pass through the second detector.

The primary difficulty in making continuum inelastic measurements is the background from the low energy tail on the elastic peak. This tail results primarily from nuclear interactions in the detector and from scattering from the solid angle defining detector apertures. By placing the detector aperture between the HE and E detectors the aperture background like the detector nuclear interaction background is limited by the ID requirement to a region in the spectrum below 10 MeV excitation. This remaining background was removed by subtracting from the data a spectrum which was obtained using a gold target at 10°. Here the elastic line (and its tail) dominate the observed spectrum.

Cross sections for Au(d,d') as a function of excitation energy at 25 and 45 deg are shown in Fig. 8.2-1. The peaks at 17.5 and 37 MeV excitation are due to hydrogen contamination in the target. The 25° spectrum shows a slight dip at 9 MeV excitation but the structure appears to be less dramatic than in inelastic measurement with p,α and \textsuperscript{3}He projectiles between 50 and 100 MeV. A common characteristic of these other measurements on heavy targets which does not appear here is a region of low cross section between 6 and 8 MeV excitation followed by a region starting at 8 MeV where the cross-section rises by a factor of 3 or 4 in about 2 MeV.

The A dependence for the total inelastic scattering cross section was found to differ significantly from the A\textsuperscript{5/2} dependence observed by Chenevert\textsuperscript{2} with (α,α') in a limited range of A. The (d,d') integrated cross sections are shown in Fig. 8.2-2 and appear to be rather independent of A. The Al point is high but a subtraction of the estimated evaporation contribution would place it at about the same level as the other masses. We have omitted our value for the 120Sn cross section from this figure pending further analysis. The tentative value for this cross section is 200 mb -- significantly higher than the others. The error bars shown in the figure arise mainly from uncertainties.
in the differential cross sections forward of 25°.

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Fig. 8.2-2. Total inelastic (d,d') cross sections at 45 MeV (integrated down to 2.5 MeV of excitation) shown as a function of mass number.

8.3 Alpha Neutron Coincidences from Bombardment of Various Targets with 90 MeV ⁴He Ions

D.R. Brown, I. Halpern, D.L. Hendrie, † and H. Homeyer ††

Last year we reported on a measurement of the differential cross section at two angles for the reaction ²⁰⁸Pb(α,5He;g.s.) at 42 MeV from which we could put a lower limit on the total cross section for this reaction of about 76 mb.¹ We also claimed that this reaction could account for part of the large bump seen in the higher energy forward angle inelastic (α,α') spectra.² During the past year we have extended our investigation to a higher energy (90 MeV) and to a number of target elements.

The measured alpha-neutron coincidence spectra at 90 MeV were far richer than the 42 MeV spectra. We report some quantitative details of the results of the measurements on ²⁰⁸Pb and mention the qualitative features of the coincidence spectra from other targets.

The new measurements were taken using the 90 MeV ⁴He ion beam from the Berkeley 88" cyclotron. Outgoing alpha particles were detected in an E-ΔE counter telescope with an angular acceptance of 4.5°. The neutron counter consisted of a 2" × 2" NE 213 organic scintillator viewed by a standard photomultiplier tube. This counter was placed 22" from the target and subtended 5.2° in the lab.

Alpha-neutron coincidence events were detected in fast coincidence and timing between the two detectors gave the relative time of flight information from which the energy of the coincident neutrons was deduced. The charged particle detection system included particle identification and pulse shape discrimi-
Fig. 8.3-1. Alpha-neutron coincidence spectrum from 90 MeV bombardment of $^{208}\text{Pb}$. Counters were nearly co-aligned at 22°. The diagonal line represents the kinematic boundary determined by the neutron separation energy of $^{208}\text{Pb}$. The contour lines on this boundary show the locations of 2 peaks in the spectrum. (The spacing between contours is 5 counts/ch.) These peaks correspond to the breakup of emitted $^5\text{He}$'s which have left $^{207}\text{Pb}$ in or near its ground state. The dashed curve gives the kinematic locus for events originating from the ($\alpha$, $^6\text{He}$) reaction in which $^6\text{He}^*$ (1.8 MeV) is formed and breaks up into $\alpha + 2n$.

A NaI scintillator was used to separate photons from neutrons in the scintillator. The data were stored event by event on magnetic tape and later converted, event by event, to XDS compatible binary for off-line analysis at NPL.

Figure 8.3-1 shows the coincidence spectrum from the bombardment of an 11.8 mg/cm$^2$ isotopic $^{208}\text{Pb}$ target measured with the alpha and neutron counters nearly co-aligned at 22°. The region in the upper right of the figure -- thinly populated with accidental counts -- lies outside the kinematic boundary determined by the neutron separation energy in $^{208}\text{Pb}$. Along this boundary one sees two peaks separated by about 12 MeV in alpha or neutron energy. Moving further left, to lower alpha energies there is a rather amorphous region of numerous events in which there is a hint of some structure and to which we return below. The spectrum was cut off by an electronic threshold set at a energy around 35 MeV.

The two peaks in Fig. 8.3-1 arise from the forward and backward break-ups of $^5\text{He}$ along its line of flight. In this case the alpha particle and neutron either add or subtract the magnitude of the internal $^5\text{He}$ momentum to their respective share of the momentum of the moving $^5\text{He}$.
The elongation of the $^5$He peaks along the kinematic boundary is due to the width of the $^5$He state ($\Gamma = 0.56$ MeV) and to breakup of $^5$He while still in the strong Coulomb field of the residual nucleus. Some of the spread in neutron energy is also due to the time resolution of the experiment ($\Delta t \approx 1.5-2$ nsec) and the short neutron flight path.

From the yield in either peak we can calculate the differential cross section for the $(\alpha,^5\text{He}^*:s^{-})$ reaction if we know the breakup angular correlation between the alpha particle and the neutron. Assuming this to be isotropic in the $^5$He frame we compute the differential cross sections from this measurement and one at a slightly greater angle to be:

$$\frac{d\sigma}{d\Omega}_5 ^5\text{He} (21.5^\circ_{\text{lab}}) = 28 \pm 7 \text{ mb/sr}$$

$$\frac{d\sigma}{d\Omega}_5 ^5\text{He} (27.5^\circ_{\text{lab}}) = 12 \pm 5 \text{ mb/sr}.$$ 

The first of these values is in reasonable accord with the value conjectured from the structure in the alpha singles spectrum observed by Chenevert.\(^2\)

The dashed curve at lower alpha energies in Fig. 8.3-1 is the kinematic locus for alpha-neutron events which result from the breakup of $^6\text{He}^8$ (1.80 MeV) ($\Gamma \approx 130$ keV). The $^6\text{He}^8:s$. is stable to particle decay, but the $2^+$ first excited state at 1.80 MeV can decay into an $\alpha$ particle and 2 neutrons with the liberation of 0.83 MeV. We first noticed two slight peaks in this region of the coincidence spectrum on the raw time of flight vs $\alpha$-energy plots of the data, where they were somewhat more conspicuous than they are in Fig. 8.3-1. These peaks appeared at the extreme alpha energies of the kinematic locus. They are presumably due to the breakup of $^6\text{He}^8(1.8)$ into an alpha particle and an unbound dineutron. Although evidence for this emission and breakup is not strong in any single one of the measured coincidence spectra because of background, the correct kinematic tracking of the enhancements as we changed detector angles supports our interpretation.

Outside the demarcated $^5$He, $^6$He\(^8\) regions, one sees numerous other events involving alphas with energies above 35 MeV and neutrons more or less uniformly distributed in energy up to about 15 MeV. There is among these events a slight hint of $^5$He formation leaving $^{207}\text{Pb}$ in higher lying excited states -- these events trail off downward and to the left from the $^5$He peaks. A large distributed background of true coincidence events was observed in all configurations where the angular separation of alpha and neutron counters was small.

Figure 8.3-2 shows the coincidence spectrum measured with the alpha counter again at 22° but with the neutron counter near the maximum possible angle for neutrons from $^5$He breakup. In this configuration the counters detect events in which the $^5$He breaks up nearly perpendicular to its line of flight. The two peaks have moved together and have spread because the large range of c.m. breakup angles detected translates into a large range of possible energies in the
Fig. 8.3-2. Alpha-neutron coincidence spectrum from 88 MeV bombardment of $^{208}$Pb. The separation in angle between the $\alpha$ and neutron counters is near the maximum it can be for the detection of $^5$He breakup events. The demarcation lines have the same meaning as in Fig. 8.3-1.

At this set of angles the kinematic locus for $^6$He$^*(1.8$ MeV) + $\alpha + 2n$ events has shrunk to the dotted line shown. Again we see a slight increase in the number of events in this region over the surroundings.

As in the spectrum shown in Fig. 8.3-1 there are numerous events outside the demarcated regions. Again there is a slight tailing of the $^5$He peaks to higher excited states of $^{207}$Pb.

Finally we show the measured coincidence spectrum with the neutron counter moved to the opposite side of the beam at about the same angle as in Fig. 8.3-2. Again the line represents the kinematic boundary for the separation of a neutron from $^{208}$Pb. The spectrum is quite barren except for some events scattered along this locus. These events probably result from the knockout of a neutron by the alpha particle.

Comparing the spectrum to those measured with the neutron counter closer to the alpha counter we see that there is a tendency for the coincident neutrons and alpha particles to appear in a common direction.

One mechanism that could lead to such a correlation and account for much of the amorphous spectrum we measure is a short-lived pick-up process in which
Fig. 8.3-3. Alpha-neutron coincidence spectrum from 90 MeV bombardment of $^{208}_{\text{Pb}}$ with counters on opposite sides of beam. The diagonal line is the kinematic boundary determined by the neutron separation energy.

The alpha particle picks up two neutrons as it goes by the nucleus - or perhaps pulls them out -- imparting some of its kinetic energy to the pair before the system breaks up. Such energetic three-body breakups would appear quite smeared out in a two particle spectrum.

We have also measured coincidence spectra with the alpha and neutron counters nearly coaligned at 22° for the bombardments of 12C, 103Rh, and NaU targets. Although these data are not fully analyzed, all coincidence spectra are similar in character to Fig. 8.3-1 in that we see peaks due to $^5\text{HeS}^-\text{S}$ and a large number of other events with alpha energies down to the electronic cutoff.

In our analysis of the $^5\text{He}$ events, we are using the DWBA with an internal wave function for $^5\text{He}$ calculated to fit the measured n-α scattering phase shifts from 0-10 MeV. The use of a scattering wave function in the $T$ matrix introduces an extra term in the phase space factor which entails an integration over the internal energy of the $^5\text{He}$ state. It is possible to separate the energy dependence of the terms in the form factor from their dependence on the α-n internal coordinate. Thus we can evaluate the $T$ matrix on resonance and carry out the integration over the internal energy separately. For these calculations we are using the finite range DWBA code LOLA written and kindly adapted for our use by Ralph DeVries.
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Hahn-Weitner Institut, Berlin, West Germany.


9. REACTIONS WITH POLARIZED PROTONS

9.1 New Fast Spin-Flip Method for a Polarized Proton Beam

E.G. Adelberger, H.F. Swanson, and T.A. Trainor

Hardware and electronic devices associated with the fast spin-flip system for the polarized ion source have been installed and successfully operated. This system was developed primarily in connection with an experiment to determine parity mixing in $^{19}$F. Because of the very small measured effect anticipated in this experiment it is important that spin-correlated beam motions on the target be eliminated as completely as possible, since these would produce a false polarization asymmetry. In principle, rapid reversal of the spin-quantization axis at the polarized source eliminates correlations with beam steering induced by operator adjustments, accelerator voltage fluctuations, and steering magnet current fluctuations. We report a modification of the fast spin-flip system which has further reduced spin-correlated beam steering.

As originally designed the system rapidly reversed the currents in two 575 G solenoids and the Helmholtz coils in the argon region of the polarized source (see Fig. 2.2-1). The axial magnetic fields corresponding to the two current polarities are shown at the top of Fig. 9.1-1 and labeled by the corresponding beam polarizations ($\mathbf{F} = +1, -1$). These magnetic fields are characteristic of a Lamb-shift source operating according to the Sona polarization scheme. Positive beam is neutralized in a cesium cell just before the quench region. Neutral beam drifts through a magnetic field crossover to the argon region where charge exchange with argon gas produces a negative ion beam.

Magnetic fields have no effect on the trajectories of the neutral beam particles. However, the charged beam entering the cesium cell and that leaving the argon cell are perturbed by the rapidly switching solenoid fields. Slight misalignment of the coils causes the fields to steer the beam. Also, because charge exchange in each case occurs within a solenoidal field, angular momentum is transferred to the beam the sense of which reverses with a reversing of the coil currents. This

Fig. 9.1-1. Polarized ion source axial magnetic fields corresponding to original Sona polarization scheme and two variations which reduce spin-correlated beam steering.
angular momentum can result in beam steering if the beam passes through rectangular slits before reaching the target. Both of these effects can produce beam motion on the target which is correlated with the spin direction.

Because the beam diameter is about four times larger in the argon cell than in the cesium cell and because the field in the argon region is about 100 times greater than that in the cesium cell it was concluded that steering effects could be sharply reduced by maintaining the argon field at one polarity in an alternative flipping scheme. This scheme is represented by the second part of Fig. 9.1-1.

In order to realize the second flipping scheme the fast spin-flip system has been modified so that each of the three coils involved in the polarization process or any combination can be separately reversed. In this scheme the field labeled $P = +1$ corresponds to the original Sona scheme. Atoms in the metastable $2s_{1/2}$ state formed in the cesium cell are quenched at point $A$ in Fig. 9.1-2. Atoms with $m_J = -1/2$ decay to the $1s_{1/2}$ state. The remaining metastable atoms pass through a field crossover at $B$ and are ionized at points labeled $C$ where they have nominally 100% nuclear polarization. If the first 575G field is reversed as in this scheme there is no longer a field crossover. Metastable atoms are ionized before passing through point $B$ and have nominally zero nuclear polarization. Thus, by rapidly reversing only the first 575G coil the polarization asymmetry can be inferred. Although the average polarization has been reduced by 1/2 as compared with the first flipping false asymmetries due to beam steering have apparently been reduced by a factor of six according to results obtained in the parity mixing experiment.

A further improvement to the flipping scheme is illustrated at the bottom of Fig. 9.1-1. It is generally recognized that the high magnetic field (100 - 200G) in the argon region necessary to realize maximum proton beam polarization in the Sona scheme may cause a substantial loss in beam current on target. This is because ionization inside the solenoidal argon field results in angular momentum pickup which degrades the beam emittance. The third scheme consists in turning off the magnetic field in the argon region and flipping both 575G solenoids. This is equivalent to ionizing atoms at point $B$ in Fig. 9.1-2. Those atoms with $m_I = +1/2$ at point $A$ remain fully polarized at point $B$ whereas metastable atoms with $m_I = -1/2$ at point $A$ have equal components with $m_I = +1/2$ and $-1/2$ at point $B$. Ionization at point $B$ thus results in an average beam polarization of 1/2. However, the beam intensity on target is doubled to compensate for the reduction in polarization. The last polarization scheme is equivalent to the adiabatic field reduction method.\(^4\)

The final fast spin-flip scheme has an additional advantage which was not
anticipated. Because of the proximity of the Wien spin precessor to the argon region there is a substantial vertical fringe field (\( \sim 2G \)) in this region. The axial argon field acting in concert with this vertical fringe field produces a net rotation of the spin out of the horizontal plane. For typical argon fields (\( \sim 200G \)) the rotation angle is 6°. For reasons discussed elsewhere in this report (Sec. 7.2) it is very important that the spin be in the horizontal plane at the target for the parity mixing experiment. Because the out-of-plane rotation caused by the Wien filter fringe field is proportional to the axial argon field intensity the third fast spin-flip scheme described here eliminates this rotation.

2. Ibid., and Sec. 7.2 of this report.

9.2 Depolarization in Elastic Scattering of 18 MeV Protons from \(^9\)Be


The existence of the spin-spin force in nucleon-nucleon scattering is well established. This force is expected to persist in the elastic scattering of nucleons from nuclei with non-zero spin. Because the force is weak relative to the central and spin-orbit forces, its influence on differential cross sections and analyzing powers is small. There is one measurable quantity, the depolarization parameter, that yields an unambiguous indication of the presence of a spin-spin interaction in elastic scattering.\(^1\) The depolarization parameter, \( D(\theta) \), is related to directly measurable quantities by the expression:

\[
D(\theta) = \frac{A(\theta) + p_1 D(\theta)}{1 + p_1 A(\theta)}
\]

(1)

where \( p_2(\theta) \) is the polarization produced at the angle \( \theta \) in the elastic scattering of an incident polarized proton beam of polarization \( p_1 \). \( A(\theta) \) is the analyzing power for elastic scattering at the angle \( \theta \). Note that for \( p_1 = 0 \), \( p_2(\theta) = A(\theta) \) as required by time reversal invariance. Also, if \( A(\theta) = 0 \), then \( p_2(\theta) = p_1 D(\theta) \), with \(-1 \leq D(\theta) \leq 1\).

Depolarization data for proton elastic scattering from nuclei are quite scarce. Catillon et al.\(^2\) have measured the depolarization parameter at one scattering angle for \(^9\)Be, \(^{10}\)B, and \(^{27}\)Al at incident energies near 20 MeV. Batty and Tschalik\(^3\) have performed similar measurements on \(^{10}\)B, \(^{59}\)Co, and \(^{205}\)Bi at energies near 50 MeV. The measurements near 20 MeV\(^2\) indicate the existence of the projectile spin-target spin interaction but a theoretical fit to the data cannot be obtained with only a scalar form for the potential.\(^1\) In order to determine the forms (e.g., tensor) and strengths of the spin-spin interactions

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involved in direct elastic scattering, a high-precision measurement of the angular distribution of \( D(\theta) \) has been undertaken.

\(^{9}\)Be has been chosen as the target for the initial measurements of the depolarization parameter because it is monoisotopic, has reasonably well-separated excited states and is relatively easy to prepare. The bombarding energy, 13 MeV, is the maximum that can be reliably achieved with the tandem accelerator and has been chosen in order that the direct reaction description of the elastic scattering will be appropriate.\(^1\) The work of Votava et al.\(^4\) indicates that the proton elastic scattering excitation functions for \(^{9}\)Be have no significant structure for bombarding energies from 13 to 15 MeV and that a standard optical model analysis provides good fits to the available differential cross section and polarization data over the range 13 to 30 MeV.

As shown in Eq. (1), the determination of \( D(\theta) \) requires the measurement of the residual polarization of incident polarized protons after elastic scattering from the target of interest. In addition, the analyzing power for the reaction, \( A(\theta) \), must be measured.

Figure 9.2-1 illustrates schematically the experimental apparatus used for the depolarization measurements. The incident beam polarization is continuously monitored by a polarimeter that consists of a 100 \( \mu \)g/cm\(^2\) C foil located about 70 cm upstream from the main target. Elastically scattered protons are detected at a laboratory angle of 55\(^\circ\) by a symmetric pair of Si(Li) counters. The measured analyzing power of the polarimeter at 18 MeV is -0.61 \pm 0.01 relative to the analyzing power of \(^{4}\)He at the same energy and a laboratory angle of 112\(^\circ\). The energy loss, multiple scattering and straggling in the C foil are negligible.

After passing through the C polarimeter, the beam is incident upon the target of interest. Reaction products from this target are detected in the Si polarimeter\(^5\) mounted on a rotatable arm in the 61 cm scattering chamber.

The polarimeter has an efficiency of 1 or 2 \( \times 10^{-5} \) and an analyzing power of \( \approx 45\% \). This type of polarimeter was built because it has excellent resolution (< 200 keV) and does not substantially degrade the overall resolution in the second-scattered spectrum. Good resolution is required for these measurements, because the targets of interest have low-lying excited states. The beam passing
through the target is collected by a split Faraday cup located directly downstream. The currents from the two halves of the cup are fed back to a regulator which controls the current in the last bending magnet and maintains the position of the beam on the target.

To test the apparatus, measurements were made with a C target substituted for the \(^9\)Be. We expect that because the ground state of \(^{12}\)C is spin 0 that \(D(\theta)\) is identically unity at all energies and angles. The results of these measurements are shown in Table 9.2-1. The uncertainties listed are purely statistical.

<table>
<thead>
<tr>
<th>Target</th>
<th>(E_p) (MeV)</th>
<th>(\theta_L)</th>
<th>(D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{12})C</td>
<td>15.5</td>
<td>55°</td>
<td>0.96±0.03</td>
</tr>
<tr>
<td></td>
<td>16.5</td>
<td></td>
<td>0.99±0.06</td>
</tr>
<tr>
<td></td>
<td>17.5</td>
<td></td>
<td>1.05±0.07</td>
</tr>
<tr>
<td>(^9)Be</td>
<td>18.0</td>
<td>80°</td>
<td>0.92±0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90°</td>
<td>0.79±0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>110°</td>
<td>0.84±0.07</td>
</tr>
</tbody>
</table>

Having established that the apparatus is functioning properly, at least to the level indicated by the uncertainties, measurements were made on \(^9\)Be at laboratory angles of 80°, 90°, and 110°. It is in this angular region that current calculations indicate some of the larger deviations in \(D(\theta)\) from unity are expected. The results of these measurements are also shown in Table 9.2-1. The deviations from unity are somewhat larger than the results of calculations based on estimates of the strength of the spin-spin interaction.

Calculations, using the DWBA code SPINSOR, are in progress to determine what forms and strengths of the spin-spin interaction are indicated by the data and to ascertain at which additional angles data should be obtained to improve the description of the scattering process.

5. Section 3.5 of this report.

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9.3

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


The extraction of cross sections and analyzing powers from measurements discussed in last year's report\(^1\) has been completed for both $^{40}$Ca and $^{48}$Ca targets. These quantities are now in hand for the reactions $^{40}$Ca($p, p'$)$^{40}$Ca (0.00) \(0^+\); (3.35) \(0^+\); (3.737) \(3^+\); (3.903) \(2^+\); (4.491) \(5^+\); (5.617) \(4^-\); (5.242 + 5.272) \(4^+ + 2^+\); (5.902) \(1^-\); (6.026) \(2^-\); (6.285) \(3^-\); and $^{48}$Ca($p, p'$)$^{48}$Ca (0.00) \(0^+\); (3.835) \(2^+\); (4.505) \(3^-\); (4.008) \(4^-\); (5.146)(4,5)\(^{-}\); and (5.729) \(5^-\), at an incident proton energy of 17.5 MeV.

The original motivation for this experiment\(^1\) was the delineation of the isospin dependence of the spin-dependent part of the interaction inducing the transition. We are presently frustrated in our attempts to deduce this dependence, however, by the poor quality of the DWBA fits to our data for either isotope.

We present in Fig. 9.3-1 the measured cross sections and analyzing powers for inelastic scattering to the following states -- $^{40}$Ca: (3.903) \(2^+\); (3.737) \(3^-\); (4.491) \(5^-\) -- $^{48}$Ca: (3.835) \(2^+\), (4.505) \(3^-\); (5.729) \(5^-\). Also shown are the predictions of the DWBA model\(^2\) which adopts a collective interaction potential incorporating a spin-dependent term of the full-Thomas form. Three special cases are presented: (a) No spin-dependence in the interaction potential, i.e., \(\beta_{L,SO} R_{SO} = 0\). (b) Equal deformations for the deformed central and spin-dependent terms, \(\beta_{L,SO} R_{SO} = \beta_{L} R_{P}\). (c) Doubled strength for the spin-dependent term, i.e., \(\beta_{L,SO} R_{SO} = 2\beta_{L} R_{P}\). In all cases, a standard spin-orbit term is included in the spherical potential used to generate the distorted waves.

The optical model parameters used in these calculations are listed in Table 9.3-1. The parameters for the $^{40}$Ca data are an extrapolation from those used by Lewellen\(^3\) to fit inelastic angular distributions, asymmetries and proton-gamma ray correlations for excitation of the 3.73 MeV \(3^-\) state by 20.3 MeV protons. The $^{48}$Ca parameters are those obtained by a group at Rutgers\(^4\) from a fit to elastic cross section and polarization data for protons of 16.25 MeV energy and less. The same parameters were used in the entrance and exit channels.

### Table 9.3-1. Optical Model Parameters (Energies in MeV, distances in F)

<table>
<thead>
<tr>
<th>(V_P)</th>
<th>(R_P)</th>
<th>(\alpha_P)</th>
<th>(W_D)</th>
<th>(R_I)</th>
<th>(\alpha_I)</th>
<th>(V_{SO})</th>
<th>(R_{SO})</th>
<th>(\alpha_{SO})</th>
<th>(R_C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$Ca</td>
<td>49.6</td>
<td>1.210</td>
<td>0.660</td>
<td>7.55</td>
<td>1.201</td>
<td>0.547</td>
<td>5.85</td>
<td>1.11</td>
<td>0.451</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>50.1</td>
<td>1.24</td>
<td>0.650</td>
<td>11.20</td>
<td>1.31</td>
<td>0.490</td>
<td>6.07</td>
<td>0.93</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Fig. 9.3-1. Inelastic angular distributions and analyzing powers for excitation of the 3.903 (2^+), 3.737 (3^-), and 4.491 MeV (5^-) levels of \(^{40}\text{Ca}\) and the 3.833 (2^+), 4.505 (3^-), and 5.729 MeV (5^-) levels of \(^{48}\text{Ca}\) by 17.5 MeV protons. The significance of the theoretical curves is discussed in the text.
The least disappointing of the fits are those for the $2^+$ excitations. The asymmetries for both isotopes suggest that $B_{21,30}^s R_{30}^s$ is greater than $B_{21} R_0$. Such a result for the $T = 0$ target $^{40}\text{Ca}$ tends to support the interpretations of Verhaar and Van Rij which attribute the greater strength of spin-dependent interaction to the fact that the range of the two-nucleon spin orbit potential is shorter than that of the two-nucleon central potential. The similar behavior for the $T = 4$ target, $^{48}\text{Ca}$, is surprising since here the $2^+$ excitation primarily involves neutron particle-hole excitations and the proton-neutron spin orbit potential is weaker than proton-proton spin orbit potential. That a collective description is tolerable for the weakly excited $2^+$ level of $^{40}\text{Ca}$ leads us to infer that the excitation proceeds through the admixture of the deformed collective band in the ground state wave function.

The failure to match the asymmetries for the $3^-$ excitations is disturbing since both excitations are thought to be rather collective and since a satisfactory account of the $^{40}\text{Ca}$ asymmetry has been given by our model when the incident energy of the protons is 20.3 MeV, only slightly higher than that of the present experiment. Neither the observed angular distributions nor the asymmetries for the $5^-$ excitations are in even qualitative accord with our calculations.

We have attempted to understand these deficiencies by proceeding in two different directions: Excitation functions for the differential cross sections have been measured for incident protons between 14.0 and 17.8 MeV at 5 selected angles. Rapid variations with energy would be a signal that a direct interaction model is not to be trusted. Only the $^{48}\text{Ca}$ data have so far been analyzed. While some structure does exist in the excitation functions for the lowest $2^+$ and $3^-$ levels, the excursions from a smooth energy dependence are not large. A naive fluctuation analysis implies that the compound nuclear contribution to the cross section is less than 5 per cent.

In addition, rather than relying on optical model parameters extrapolated from analyses at other energies, we are in the process of obtaining fits to the elastic scattering data for the incident energy of this experiment. We believe that some of our difficulties accrue to the present choice of parameters, since, particularly for $^{40}\text{Ca}$, this choice provides a rather poor fit to the measured elastic asymmetry. If the newer optical parameters do not remove the leading discrepancies between the inelastic data and calculations, it is likely that we will investigate the energy dependence of the inelastic asymmetries themselves.

9.4 Analyzing Power in the $^{206}\text{Pb}^+ (p, p_0)^{206}\text{Pb}$ Reaction near the $3p_{1/2}$ Isobaric Analog Resonance


Accurate experimental values of the resonance mixing phases of isobaric analog resonances (IAR) provide stringent tests of current IAR theories. The theoretical calculations are expected to be most accurate for IAR in compound nuclei near closed shells.\(^1\) The resonance parameters for the IAR near $A = 90$ and $A = 140$ have been determined recently by the Erlangen group.\(^2\) They find the resonance mixing phases to be quite small (≈ 5°). A measurement in the Pb region is needed to give a more complete summary of the experimental results. Careful measurements have been completed for the IAR in $^{209}\text{Bi}$,\(^3\) but the accurate extraction of the resonance mixing phases is difficult because the resonances are closely spaced relative to their widths. The situation is considerably improved for the $3p_{1/2}$ g.s. IAR in $^{207}\text{Bi}$ since this resonance is separated from the major resonances at higher energies by the shell gap.

Analyzing power excitation functions and angular distributions have therefore been obtained for elastic proton scattering on $^{206}\text{Pb}$ in the vicinity of the $3p_{1/2}$ IAR. An accurate determination of both the resonance mixing phase and the elastic partial width can be made from such analyzing power measurements since the off-resonance analyzing power is very small.

\[ E_p \quad 14.92 \quad 9p_1^+ \]
\[ 13.10 \quad 8p_2 \]
\[ 12.78 \quad 7s_1^+ \]

Figure 9.4-1 shows a schematic energy level diagram for the $A = 207$ system. On the right, some of the low-lying states of $^{207}\text{Pb}$ are illustrated. In the middle are their isobaric analogs labeled with the laboratory bombarding energies necessary to reach them. The $8g_9/2$ state shown is in the next shell. The $f_{5/2}$ and $p_{3/2}$ states are also expected to be considerably weaker than the $p_{1/2}$ state.

The excitation functions were obtained at $120^\circ$, $150^\circ$ and $180^\circ$ for proton bombarding energies between 11.0 and 13.6 MeV in 50 or 100 keV steps. The target was isotopically enriched, self-supporting $^{206}\text{Pb}$ approximately 400 μg/cm² gram for $A = 207$.

Fig. 9.4-1. Schematic energy level diagram for the $A = 207$ system.
thick. Left-right asymmetries were measured with symmetric Si(Li) detector pairs with acceptance angles of \( \pm 2^\circ \). The beam polarization was continuously monitored by measuring left-right asymmetries of protons elastically scattered from \(^{4}\)He at \(112^\circ\). To reduce instrumental corrections, the asymmetries were measured twice at each energy, once with the incident beam spin up and once with the spin down.

The excitation functions obtained are shown in Fig. 9.4-2. The target thickness for beams of this energy is about 6 keV. The statistical uncertainties are generally 1% or less. Structure due to the \(3p_{1/2}\) resonance at 12.2 MeV is clearly seen at all three angles, with the most distinctive resonance effect observed at \(120^\circ\). Because the elastic scattering partial width is only a fraction of the total width and the resonance occurs near the Coulomb barrier, the maximum measured polarization is approximately 10%. The curves in Fig. 9.4-2 are calculations of the analyzing power incorporating the optical model to generate the potential scattering background and a Breit-Wigner term to describe the resonance. The optical model parameters were taken from the analysis of proton elastic scattering on \(^{208}\)Pb at 12.98 MeV of Rathmell and Haeberli. Both the real and imaginary potential well depths used have a linear energy dependence as suggested by Becchetti and Greenlees. The total width of the resonance was taken from the results of the differential cross section measurements for proton inelastic scattering of Richard et al. The resonance energy and elastic partial width were adjusted to give a reasonable fit to the data although no formal search was made. Two curves are shown for each angle, one with the resonance mixing phase, \(\phi_R\), set equal to \(0^\circ\), the other with \(\phi_R = 15^\circ\). The resonance energy used in the calculations is about 25 keV less than that given in Ref. 6. The \(120^\circ\) data are the most sensitive to changes in the overall phase of the \(p_{1/2}\) amplitude. The \(\phi_R = 0^\circ\) calculation seems to give a much better fit to the data at this angle. The phase of the \(p_{1/2}\) amplitude, however, also depends upon the real part of the \(p_{1/2}\) optical model phase shift \((2\lambda_{p_{1/2}})\). For the optical model parameters used

Fig. 9.4-2. Analyzing power excitation functions for \(^{206}\)Pb(\(p, p_0\))\(^{206}\)Pb in the vicinity of the \(3p_{1/2}\) \(1^+\)AR.
here $2\lambda_{1/2} = 7^\circ$. Since this phase is quite small, variations in optical model parameters are not expected to cause large changes in its magnitude. The resonance parameters obtained from this procedure are given in Table 9.4-1.

<table>
<thead>
<tr>
<th>$E_R$</th>
<th>$\Gamma_p$ (keV)</th>
<th>$\Phi_R$</th>
<th>$\Gamma_T$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.204</td>
<td>18 $\pm$ 3</td>
<td>5 $\pm$ 7</td>
<td>170</td>
</tr>
</tbody>
</table>

Table 9.4-1. Resonance parameters obtained from fit to $^{206}\text{Pb}(p,p_0)^{206}\text{Pb}$ excitation functions.

In order to learn more about the potential scattering background, elastic scattering angular distributions were measured at bombarding energies of 11.5 and 12.75 MeV. These energies are somewhat lower and somewhat higher than those at which the maximum resonance effects are observed. The experimental procedures were the same as for the excitation function measurements. The angular distributions obtained are shown in Fig. 9.4-3. The curves shown are again optical model calculations with a Breit-Wigner term included for the resonance. The

Fig. 9.4-3. Off-resonance differential cross section and analyzing power angular distributions for $^{206}\text{Pb}(p,p_0)^{206}\text{Pb}$. 
optical model parameters used are those of Ref. 4 and the resonance parameters are the same as those obtained from the fit in Fig. 9.4-2. An optical model search is in progress in order to improve the fit to these data. The optical model parameters obtained from such a search should improve the description of the background and reduce the uncertainty in the resonance parameters extracted from the excitation function data. If some ambiguity still remains in the resonance parameters, the total width and resonance energy can be obtained independently from an accurate measurement of inelastic scattering cross section excitation functions in the vicinity of the resonance. This is possible because the direct inelastic scattering background is usually much lower than in the elastic scattering case and can be parameterized in a very simple fashion.

A nearly model-independent determination of the relative spectroscopic factor (SF) for this state can be obtained by forming the ratio of the measured elastic scattering partial widths for the ground state analogs in $^{207}$Pb and $^{208}$Pb. It is anticipated that the $^{207}$Pb ground state is essentially pure $P1/2$ hole and therefore the absolute spectroscopic factor for forming the $^{208}$Pb ground state IAR is near unity. A correction for energy dependence must be applied to this ratio since the ground state IAR in $^{207}$Pb occurs at 12.20 MeV while in $^{208}$Pb it is at 11.55 MeV. This correction was determined by calculating the $3p1/2$ single-particle widths for the $^{207}$Pb and $^{208}$Pb ground state IAR using the code ANALOG. The proton scattering wave function was described by the optical model parameters given in Sec. 9.5 of this report. The neutron bound state central potential well had a radius of 1.17 $\text{fm}$ and a diffuseness of 0.83 $\text{fm}$. The spin-orbit potential was defined by the same parameters as for the proton scattering wave function. The central potential well depth was adjusted to reproduce the neutron binding energy for each case.

The results of this procedure are given in Table 9.4-2. Taking the energy dependence from a theoretical calculation appears justifiable in that this calculation yields an absolute spectroscopic factor for the $^{208}$Pb ground state IAR which is unity within the experimental uncertainty. The relative spectroscopic factor, 0.50, for the $^{207}$Pb ground state IAR can be compared to the recent results of Lamford and Crawley. They compare the $^{207}$Pbd$^{206}$Pb cross sections to the $^{208}$Pbd$^{207}$Pb cross sections for the single-hole states. Small corrections for Q-value dependence are made using DWBA. Their relative spectroscopic factor for the ground state transitions is then 0.59. The IAR and pickup results are in good agreement.

### Table 9.4-2. Calculated and experimental resonance parameters and derived spectroscopic factors for $^{208}$Pb and $^{207}$Pb ground state IAR

<table>
<thead>
<tr>
<th>Parent</th>
<th>$E_R$ (MeV)</th>
<th>$I_{\text{calc}}$ (keV)</th>
<th>$\phi_{\text{calc}}$</th>
<th>$I_{\text{exp}}$ (keV)</th>
<th>$S_{\text{abs}}$</th>
<th>$S_{\text{rel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}$Pb($0^+$)</td>
<td>11.55</td>
<td>55.6</td>
<td>21.0°</td>
<td>56±3</td>
<td>1.0±.05</td>
<td>≈ 1</td>
</tr>
<tr>
<td>$^{207}$Pb($1/2^-$)</td>
<td>12.20</td>
<td>36.1</td>
<td>21.9°</td>
<td>13±3</td>
<td>.50±.08</td>
<td>.50±.09</td>
</tr>
</tbody>
</table>
Also shown in Table 9.4-2 are the calculated results for the resonance mixing phases. Those are much larger than the current experimental results indicate.

1. Section 9.5 of this report.

9.5 Spectroscopic Analysis of Proton Elastic Scattering from $^{208}$Pb near the Low-Lying Isobaric Analog Resonances


As reported previously, analyzing power and differential cross section excitation functions have been measured for proton elastic scattering from $^{208}$Pb in the region of the low-lying isobaric analog resonances (IAR). These were made in order that accurate elastic scattering partial widths could be determined for precise comparison to corresponding theoretical predictions. Such comparisons provide information on the extent to which the shell model can reliably predict the details of nuclear structure in this region.

The elastic scattering partial widths were determined by parameterizing the potential scattering background, adding in Breit-Wigner terms for the IAR and searching simultaneously on the background and resonance parameters. The results of this procedure are shown in Table 9.5-1.

As a consistency check on the appropriateness of a parameterized potential scattering background, an optical model search has been performed. Breit-Wigner terms, to describe the resonances, were added to the usual S-matrix background terms and the resonance parameters were held fixed at the values obtained from the parameterized fit. Starting with the Becchetti-Greenlees’ global parameter set, the optical model parameters were allowed to vary in order to fit simultaneously the analyzing power and differential cross section data at 500 keV intervals across the 14-18 MeV proton bombarding energy range of interest. The fit obtained is shown in Fig. 9.5-1 along with the fits determined by parameterizing the potential scattering backgrounds at each angle independently. The solid dots are the data reported previously.
Table 9.5-1. Experimental and theoretical elastic scattering partial widths and derived spectroscopic factors for the IAR of 209Pb.

<table>
<thead>
<tr>
<th>E_{cm}</th>
<th>n_{lj}</th>
<th>\Gamma_{exp}(keV)</th>
<th>\Gamma_{th}(keV)</th>
<th>S(IAR)</th>
<th>S(d,p)</th>
<th>\Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.846</td>
<td>g_{9/2}</td>
<td>21 ± 2</td>
<td>20.4</td>
<td>1.04 ± .10</td>
<td>.91</td>
<td>253 ± 10</td>
</tr>
<tr>
<td>15.646</td>
<td>i_{11/2}</td>
<td>2.0 ± 0.3</td>
<td>2.4</td>
<td>.84 ± .13</td>
<td>1.2</td>
<td>224 ± 20</td>
</tr>
<tr>
<td>16.416</td>
<td>d_{5/2}</td>
<td>50 ± 2</td>
<td>50.5</td>
<td>1.00 ± .04</td>
<td>.89</td>
<td>308 ± 8</td>
</tr>
<tr>
<td>16.883</td>
<td>s_{1/2}</td>
<td>49 ± 4</td>
<td>54.0</td>
<td>.91 ± .07</td>
<td>.91</td>
<td>319 ± 15</td>
</tr>
<tr>
<td>17.346</td>
<td>g_{7/2}</td>
<td>30 ± 4</td>
<td>33.8</td>
<td>.90 ± .12</td>
<td>1.1</td>
<td>288 ± 20</td>
</tr>
<tr>
<td>17.392</td>
<td>d_{3/2}</td>
<td>47 ± 7</td>
<td>51.1</td>
<td>.93 ± .14</td>
<td>.97</td>
<td>279 ± 20</td>
</tr>
</tbody>
</table>

The optical model parameters that resulted from the search are shown in Table 9.5-2. The general agreement between the two methods of describing the background scattering is very good.

Table 9.5-2. Proton optical model parameters determined from fit to \(^{208}\text{Pb}(p,p'_{0})^{208}\text{Pb}\) excitation functions. Potential well parameter units are as follows:

- Well depth: MeV
- Diffuseness: F
- Radius: \(A^{-1/3}\)

<table>
<thead>
<tr>
<th>(V_r)</th>
<th>(r_r)</th>
<th>(a_r)</th>
<th>(W_s)</th>
<th>(r_I)</th>
<th>(a_I)</th>
<th>(V_{so})</th>
</tr>
</thead>
<tbody>
<tr>
<td>61.39-32 (E_{lab})</td>
<td>1.19</td>
<td>.83</td>
<td>16.80-25 (E_{lab})</td>
<td>1.30</td>
<td>.66</td>
<td>6.2</td>
</tr>
</tbody>
</table>

In addition to the excellent fit obtained for the elastic scattering excitation functions, support for this optical model potential is given by the measurements of Thomas and Bartolini.\(^3\) They have determined the sum of \(\sigma(p,n)\), \(\sigma(p,\alpha)\) and \(\sigma(p,2\alpha)\) in the energy region 7.6 - 13.9 MeV. An extrapolation of their excitation function to 14 MeV gives 835±50 mb for this sum. If we assume
Fig. 9.5-1. Analyzing power and differential cross section excitation functions for $^{208}\text{Pb}(\vec{p},p)^{208}\text{Pb}$. The curves are theoretical fits to the data with the direct elastic scattering generated from the optical model or parameterized by polynomials in energy.

that the sum of the cross sections for these three processes is essentially the total reaction cross section, then we can compare the experimental value to that calculated from the optical model. For the parameters listed in Table 9.5-2 we calculate 850 mb for the total reaction cross section at 14 MeV.

Having an adequate phenomenological description of the elastic scattering process, calculations, based on the theory of Bund and Blair, were made for the single particle widths of these IAR using the code ANALOG. The proton scattering wave function was determined from the optical model potentials in Table 9.5-2.

The neutron bound state central potential well had a radius of 1.17 $\text{A}^{1/3}$ F and a diffuseness of .83 F. This choice of $\rho_0$ results in the observed resonance energy of each IAR being equal to the sum of the Coulomb shift of the IAR and the calculated displacement energy. The spin-orbit potential was defined by the same parameters as for the proton scattering wave function. The central potential well depth was adjusted to reproduce the neutron binding energy for each parent state.

This procedure yielded the calculated partial widths given in Table 9.5-1. The values shown include small corrections for the energy variation of the displacement energies. The ratio ($\exp/\mathbf{th}$) is then the spectroscopic factor (SF) for a given state. Almost all of the SF are consistent with unity. The SF obtained from a recent DWBA analysis of $^{208}\text{Pb}(d,p)^{209}\text{Pb}$ differential
cross section measurements at 12.3 MeV are also shown in Table 9.5-1 for comparison. The uncertainty in the differential cross section scale for the (d,p) reaction is claimed to be ±10%.

In conclusion, the disagreement in the literature\textsuperscript{1} over the values of the elastic scattering partial widths for the IAR of the low-lying states of $^{209}$Pb has been resolved. The partial widths determined in this study, when compared to theoretical calculations, give SF equal to unity within experimental uncertainties. These SF for the IAR are in agreement with those determined from (d,p) reactions to the parent states.

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9.5 The Analyzing Power for Elastic Scattering of Protons from $^{12}$C


Measurements of the analyzing power for elastic scattering of protons from carbon are of interest because they can be used to determine more clearly background and resonant phase shifts than can differential cross section measurements alone. This is because the analyzing power is determined by a combination of complex phase shifts which is independent of the combination which determines the differential cross section. The lack of accurate background phase shifts prevented a complete description of the various levels seen in the differential cross section data of LeVine and Parker.\textsuperscript{1} In addition, the acquired analyzing power information can facilitate the use of carbon as a polarization analyzer in other experiments.

Differential cross section and analyzing power excitation functions have been measured between 11.5 and 17.7 MeV at three backward angles. These angles were chosen on the basis of cross section behavior in this energy region. In addition, six angular distributions were obtained to aid in the determination of resonant and background phase shifts.

Protons scattered from the target were detected by three pairs of surface barrier detectors placed symmetrically about the beam axis as in Fig. 9.6-1. Natural carbon targets of about 2 mg/cm$^2$ thickness were used. The beam polarization was continuously monitored by a $^4$He polarimeter downstream from the carbon target. The beam polarization was typically 65%. At every angle setting, alternate runs of equal integrated beam current with spin up and spin down were taken. The statistical uncertainty in the analyzing power is better than .01 in nearly all cases. Our analyzing power data at 11.5 MeV is in good agreement with that
Fig. 9.6-2. Analyzing power excitation functions for three back angles in the reaction $^{12}\text{C}(\vec{p},p_0)$ from 11.5 to 17.7 MeV.
of Meyer and Plattner. 2

Structure in the analyzing power is easily seen at the 13.04 MeV 3/2− and 15.22 MeV 7/2+ states. It is interesting to note that the analyzing power at 160° lab angle in the vicinity of 14.8 MeV is very nearly 1.0 which might allow the use of carbon as an absolute polarization analyzer in this region. In addition a prominent dip is seen at about 11.9 MeV in all three back angle excitation functions. Little evidence of this structure can be seen in differential cross section data. 1

Presently, a phase shift search is in progress to derive background phase shifts for the entire energy region. Special emphasis is being placed on determining the nature of the structure at 11.9 MeV.


---

**Fig. 9.6-1.** Experimental setup for analyzing power measurements.

**Fig. 9.6-3.** Angular distribution of the analyzing power for the $^{12}\text{C}(\text{p},\text{p}_0)^+$ reaction at 14.8 and 17.2 MeV.
10. HEAVY ION REACTIONS

10.1 The Importance of Coulomb Interaction Potentials in Heavy Ion DWBA Calculations

J.G. Cramer, R.M. DeVries, and C.R. Satchler

The transition amplitude for a transfer reaction \( A(a,b)B \) (with \( a = b + x \), \( B = A + x \)) is given by the distorted wave Born approximation (DWBA) as:

\[
T = \int dr_a dr_b \chi^+_b(r_b) \psi_b^{(+)}(r_b) \psi_a^{(+)}(r_a) \chi^+_a(r_a) \Delta V\psi_a^{(+)}(r_a) \psi_b^{(+)}(r_b) \chi^+_b(r_b)
\]

where \( \chi \) are the distorted waves, \( \psi \) are the bound state wave functions, and the vector coordinates are defined by the diagram shown in Fig. 10.1-1. The interaction potential \( \Delta V \) which produces the transition consists of a nuclear and Coulomb part, i.e.,

\[
\Delta V = \Delta V^N + \Delta V^C.
\]

In the post representation these terms are written:

\[
\Delta V^N = V^N_{bx}(r_b) + V^N_{bx}(r_x) - U^N_{bx}(r_b)
\]

\[
\Delta V^C = V^C_{bx}(r_b) + V^C_{bx}(r_x) - U^C_{bx}(r_b)
\]

and in the prior representation:

\[
\Delta V^N = V^N_{xa}(r_a) + V^N_{xa}(r_x) - U^N_{xa}(r_a)
\]

\[
\Delta V^C = V^C_{xa}(r_a) + V^C_{xa}(r_x) - U^C_{xa}(r_a)
\]

The superscript \( C \) denotes the Coulomb term in the interaction, \( U \) is the optical potential for the respective channels, the potential \( V_{bx} \) and \( V_{xa} \) are the bound state potentials and \( V_{ba} \) is the core-core potential. In almost all DWBA calculations the interaction potential is taken in the post form and approximated by \( \Delta V = V^N_{bx} \) with neither the Coulomb terms nor the last two terms in (3) included.

In the work reported here we have investigated the effect of including all three of the Coulomb terms (4) and (6). Calculations exactly evaluating this contribution have not been

Fig. 10.1-1. The vector diagram for coordinates used in the DWBA calculation.
previously reported, although some approximate treatments have been made.\textsuperscript{1,2}

The difficulty is that the exact treatment requires the proper handling of their vector coordinates (Fig. 10.1-1) which can only be done by the inclusion of "recoil effects", i.e., evaluation of the full six dimensional integral in (1), as is done in the finite range DWBA program LOLA,\textsuperscript{3} a modified version of which was used in this work.

To evaluate the Coulomb terms in (4) or (6) we use the usual form for the Coulomb potential of a spherical charge distribution:

\[ V_{\text{Coul}}(r) = \begin{cases} 
  z_1 z_2 e^2 \left( \frac{1}{2} \frac{3}{R_C} - \frac{r^2}{R_C^3} \right) & r \leq R_C \\
  z_1 z_2 e^2 / r & r > R_C
\end{cases} \]  

(7)

Thus the only parameters involved are the radii $R_i$. These are taken to be the same as the radii for the bound states for the first term of (4) and (6) and the same as the optical model radii for the last two terms. The results were found to be insensitive to the actual values used. Note that for neutron transfers, the first term in (4) or (6) vanishes because $z_n = 0$ and the last two terms differ only slightly and thus nearly cancel. Therefore we expect that $\Delta V^C$ will be more important for charged particle transfer than for neutron transfer. In addition we might expect that $\Delta V^C$ will be more important in the prior form than in the post form because of the larger charge products involved. We find that the inclusion of the $\Delta V^C$ term dramatically affects two areas of heavy ion DWBA calculations: the post-prior dilemma and the energy dependence of DWBA calculations. These effects are seen mainly in the magnitudes of the predicted cross sections; generally the differences in the predicted shapes is quite small.

Buttle and Goldfarb\textsuperscript{1} showed that non-recoil DWBA calculations (including Coulomb terms approximately) gave a strong discrepancy between the theoretically equivalent post-prior representations which was at least partially solved by the approximate inclusion of recoil. Indeed, calculations using only the leading terms in (3) or (5) for heavy ion single nucleon transfer reactions on light targets show no post-prior discrepancies if recoil is included exactly.\textsuperscript{3} However, for heavier targets discrepancies as large as 57% still exist, as shown in Table 10.1-1. This is of more than academic interest since the aim is to deduce spectroscopic factors with much better accuracy than this. Table 10.1-1 shows that the inclusion of $\Delta V^C$ reduces the discrepancy to more acceptable levels.

These results can be understood by examining the terms in a typical case, say the $^{208}\text{Pb}(^{11}B,^{16}Be){}^{209}\text{Bi}$ reaction at 72.2 MeV. The transfers take place predominantly when the two cores are separated by about 12 fm. The transferred particle does not deviate far from the line joining the centers of the two cores. In the post form, the important contributions come when $x$ is close to $b$, $r_{bx} \approx 2$ to 3 fm; in the prior form, this region moves closer to $A$, with $r_{xA}$ perhaps 8 to 10 fm. When a neutron is transferred, the post $V^C$ then has a value of 100-200 keV compared to the nuclear interaction $V_{nx}$ of several tens of MeV, while the prior $\Delta V^C$ is approximately zero. In proton transfer, however, the post $V^C$ term
Table 10.1-1. Peak cross sections in arbitrary units with and without the Coulomb interaction potentials.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>EI (MeV)</th>
<th>θ (°)</th>
<th>Prior</th>
<th>Post</th>
<th>R</th>
<th>Prior</th>
<th>Post</th>
<th>R</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>88Sr(160, 2N)89Y</td>
<td>59</td>
<td>70°</td>
<td>.146</td>
<td>.107</td>
<td>1.36</td>
<td>.0819</td>
<td>.0780</td>
<td>1.038</td>
<td>0.581</td>
</tr>
<tr>
<td>88Sr(160, 2N)89Y</td>
<td>48</td>
<td>135°</td>
<td>.0527</td>
<td>.0467</td>
<td>1.34</td>
<td>.0353</td>
<td>.0264</td>
<td>1.024</td>
<td>0.163</td>
</tr>
<tr>
<td>208Pd(160, 15N)206Bi</td>
<td>104</td>
<td>68°</td>
<td>.231</td>
<td>.186</td>
<td>1.40</td>
<td>.149</td>
<td>.139</td>
<td>1.065</td>
<td>0.167</td>
</tr>
<tr>
<td>208Pb(11B, 10Be)206Bi</td>
<td>72.2</td>
<td>52°</td>
<td>.703</td>
<td>.493</td>
<td>1.57</td>
<td>.443</td>
<td>.417</td>
<td>1.062</td>
<td>0.166</td>
</tr>
<tr>
<td>208Pb(11B, 8Bi)206Bi</td>
<td>72.2</td>
<td>56°</td>
<td>.231</td>
<td>.318</td>
<td>0.76</td>
<td>.340</td>
<td>.324</td>
<td>1.049</td>
<td>1.411</td>
</tr>
</tbody>
</table>

b) D.S. Kovar, B.G. Harvey, F.D. Becchetti, J. Mahoney, E.L. Hendrie, H. Heuser, W. von Oertzen, and
c) G.R. Satchler et al., to be published.

is between 1 and 2 MeV in the important region while the other Coulomb terms are about \(-1/2\) MeV, thus reducing the first term by about 40\%, typically. In the prior case the \(V_{\text{NC}}\) term is of the order of 10 MeV in the important region, comparable to the nuclear \(V_{\text{NC}}\) term, while it is easy to see that the remaining Coulomb terms are comparable, but of opposite sign so there is very considerable cancellation.

Apparently the remaining few percent post-prior discrepancy is due to the neglect of the term \(U_{\text{opt}}^N\) in (2) or (5) (since \(V_{\text{DA}}\) is common to both forms). That this is indeed reasonable has been demonstrated by turning off all Coulomb forces in the DWBA calculations (i.e., setting all \(z = 0\)) in which case we are neglecting only the last two nuclear interaction terms. For this case the post and prior agree to better than 1\% at the peak cross section angle with a slow deterioration at larger angles. The difference is never greater than 1\% of the peak cross section.

A test of the code may be performed by including the \(U_{\text{opt}}^N\) term in both post and prior. We then are including 5 out of the 6 terms exactly, leaving out, in both post and prior, only the same potential \(V_{\text{DA}}^N\). We have done this for the reaction \(208\text{Pb}(160, 15N)206\text{Bi}\) producing cross sections (to be compared with Table 10.1-1) of .1256 in the prior form and .1263 in the post form. This leaves a post-prior difference of 0.59\% which may be attributed to small numerical computational errors and is not felt to be excessive. Thus \(U_{\text{opt}}^N\) produces about a 10\% change in cross section in the post form (20\% in the prior form). In a full (six interaction term) calculation this \(U_{\text{opt}}^N\) would be at least partially cancelled by the \(V_{\text{DA}}^N\) term, therefore, for the type of reactions discussed in this paper it is reasonable to neglect the last two nuclear interaction terms in (3) or (5), but not the Coulomb terms of (4) or (6). Studies of the effect of the remaining term \(V_{\text{NC}}^N\) are limited by the fact that the correct form of the potential
is not known.

We have also studied the energy dependence of the DWBA predictions in the post representation with and without $\Delta V^C$. The results are summarized in Fig. 10.1-2 for single nucleon stripping reactions on $^{28}$Si. The ratio represents the correction which needs to be applied to spectroscopic factors obtained with only the $W_N$ interaction term. It has generally been assumed that heavy ion induced reactions analyzed with the DWBA should yield spectroscopic factors in agreement with those found in light ion experiments. This assumption should be correct for neutron transfer reactions as Fig. 10.1-1 shows that the Coulomb interaction term affects these reactions very little and without any marked energy dependence. This is not the case, however, for charged particle transfer. These spectroscopic factors can be accurately compared between light and heavy ion reactions only if the heavy ion incident energy is at least 1.5-2 times the Coulomb barrier energy, or if the DWBA calculation used includes the $\Delta V^C$ interaction terms. This conclusion and the magnitude of the effect are found to be essentially the same for other targets and angular momentum transfers. As might be expected the energy dependence in the prior representation is even more striking, but of less importance since all light ion reaction analyses use the post representation implicit in the use of the zero-range approximation.

In conclusion we find that the interaction potentials appropriate to DWBA analyses of heavy ion transfer reactions must include the normally neglected Coulomb terms if accurate results are desired. We should emphasize that any DWBA calculation which includes a difference between the post and prior forms includes that amount of uncertainty in its predictions. This post-prior difference is sharply reduced if the Coulomb terms are included. We are studying other types of reactions and various approximation schemes for these interaction potentials.

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10.2 Recoil Corrections in DWBA Calculations of Heavy Ion Transfer Cross Sections

A.J. Baltz, J.S. Blair, R.M. DeVries, K.G. Nair, and W. Reisdorf

A bewildering variety of DWBA codes have been constructed to analyze heavy ion transfer cross sections. Most of these involve further approximations beyond the basic DWBA itself. Since the few exact DWBA codes tend to be costly to run and frequently tax the memory capabilities of available computers, these more approximate calculations have found much use. Consequently, it is worthwhile to inquire how accurate are these calculations.

The present work compares numerically exact DWBA calculations to some of the more approximate calculations in order to discover the limits of accuracy of the latter. The calculations of DeVries, which treat finite range and recoil effects exactly, define the standard. The other treatments here considered are: a. The finite range but no-recoil procedure of Sawaguri and Tobocman as programmed by Schmittroth, Tobocman, and Colestanek. b. The extension of this by Baltz and Kahana which includes exactly first order recoil effects. c. The method of Buttle and Goldfarb with and without their approximate correction for recoil. d. An extension of this by Reisdorf which includes exactly first order recoil effects. e. An analytic approximation to the Buttle-Goldfarb formulas, relevant only to sub-Coulomb reactions.

The reactions considered as test cases were: $^{88}$Sr($^{16}$O, $^{15}$N)$^{89}$Y (g.s. and 0.91 MeV), which typify proton transfer to a moderately heavy target with a good "Q-match", for E(lab) between 42.5 and 59 MeV. $^{30}$Si($^{16}$O,$^{15}$N)$^{31}$p (g.s. and 1.26 MeV), which typify proton transfer on lighter targets with a less favorable Q-match, for E(lab) = 25, 30, 42, and 60 MeV. $^{40}$Ca($^{16}$O,$^{12}$C)$^{44}$Ti (g.s.), an alpha particle transfer reaction, at 42 MeV. In each case, common optical model and bound state parameters are adopted for the comparisons.

A sense of the accuracy of the various calculations may be gained from the following truncated table giving ratios of peak cross sections to those of DeVries:

<table>
<thead>
<tr>
<th>Final State</th>
<th>E(lab) (MeV)</th>
<th>Peak angle (Degrees)</th>
<th>BK (Ref.4)</th>
<th>R (Ref.6)</th>
<th>BG With Rec</th>
<th>BG Sub-Coul</th>
<th>BG No Rec</th>
<th>STSG (Ref.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{89}$Y(g.s.)</td>
<td>46</td>
<td>170(^o)</td>
<td>.98</td>
<td>1.01</td>
<td>1.01</td>
<td>1.13</td>
<td>.92</td>
<td>.69</td>
</tr>
<tr>
<td>L = 0</td>
<td>59</td>
<td>70</td>
<td>1.02</td>
<td>1.05</td>
<td>1.09</td>
<td>NA</td>
<td>.88</td>
<td>.66</td>
</tr>
<tr>
<td>$^{89}$Y(0.91)</td>
<td>46</td>
<td>170</td>
<td>.96</td>
<td>1.05</td>
<td>1.06</td>
<td>1.18</td>
<td>.86</td>
<td>.63</td>
</tr>
<tr>
<td>L = 5</td>
<td>59</td>
<td>75</td>
<td>1.06</td>
<td>.99</td>
<td>1.08</td>
<td>NA</td>
<td>1.09</td>
<td>.82</td>
</tr>
<tr>
<td>$^{31}$P(g.s.)</td>
<td>30</td>
<td>105</td>
<td>.92</td>
<td>.95</td>
<td>1.14</td>
<td>NA</td>
<td>.69</td>
<td>.53</td>
</tr>
<tr>
<td>L = 1</td>
<td>60</td>
<td>25</td>
<td>1.03</td>
<td>1.14</td>
<td>1.63</td>
<td>NA</td>
<td>.95</td>
<td>.73</td>
</tr>
<tr>
<td>$^{31}$P(1.26)</td>
<td>30</td>
<td>115</td>
<td>.81</td>
<td>.77</td>
<td>.67</td>
<td>NA</td>
<td>.38</td>
<td>.30</td>
</tr>
<tr>
<td>L = 1</td>
<td>60</td>
<td>25</td>
<td>.87</td>
<td>.88</td>
<td>.59</td>
<td>NA</td>
<td>.29</td>
<td>.22</td>
</tr>
<tr>
<td>L = 2</td>
<td>60</td>
<td>20</td>
<td>.71</td>
<td>.73</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
A fuller comparison as well as descriptions of the various approximations and
details of the calculations are contained in a paper nearing completion.

Inspection of our full results leads us to conclude: (a) The extensions
of BK and of R may be applied to a wide range of single nucleon transfer reac-
tions with an accuracy generally better than 10%. (b) The recoil prescription
of BG is not so reliable above the barrier when the Q-match is poor. (c) The
analytic sub-Coulomb expression of BG is useful only when the Q-match is good.
(d) Calculations which ignore recoil are distinctly inferior. (e) In addition,
one of the approximate calculations gave accurate α-transfer cross sections.

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† Currently at Laboratoire Rene BERNAS, Orsay, France, where part of this
work was done.
3. F. Schmittroth, W. Tobocman, and A.A. Golestaneh, Phys. Rev. C 1, 337
Munich, 425.

10.3 Analysis of the $^{12}$C($^{12}$C, $^8$Be)$^{16}$O Reaction near $E_{c.m.}$ = 5.0 MeV

M.D. Cooper

Last year $^1$ we reported on the measurement of the $^{12}$C($^{12}$C, $^8$Be)$^{16}$O partial
cross sections for the angular momenta 0, 2, and 4. The most distinctive feature
in the excitation function was in the $l = 4$ channel, where the $4^+$ resonance ap-
ppeared to be interfering with a non-resonant background. We have attempted to
fit the energy dependence of the cross section in terms of R-matrix theory and to
use the deduced reduced width to interpret the significance of this channel in
terms of the quasi-molecular model. A large reduced width, comparable to that
for the elastic channel, would support an alpha transfer for this state.

The original analysis $^2$ of the elastic and alpha-particle channels used
Coulomb waves to calculate the penetrabilities and to evaluate the reduced widths.
It was quite obvious that the penetrabilities for the elastic channel depended
strongly on the value of the R-matrix matching radius, but since the reduced
width for the $^{12}$C channel was always at least a factor of 20 greater than for any
other channel, the quasi-molecular model still seemed valid. The 1.1 keV partial
width for the $^8$Be channel, if analyzed by similar techniques, corresponds to a
reduced width ranging from one nearly equal to that of the elastic channel to
one similar to the alpha-particle reduced widths, depending on the radius chosen.
Since such an ambiguity clouds the interpretation, we have attempted to use a
more complete theory to remove the uncertainty.
The technique described here is an attempt to remove the radius ambiguity by including the tail of the nuclear potential in the calculation of the $R$-matrix wave functions via the optical model. This theory was quite successfully applied to isobaric analog states$^3$ and it is hoped that it will be useful here.

Following the notation of Ref. 3, we restate their results; we have not specialized to elastic scattering. Our object is to derive a collision matrix in the generalized theory, whose square is proportional to the cross section, which will allow us to fit the transfer cross section and to extract reliable reduced widths. The result for a single resonance plus background is

$$
U_{cc'} = [2e^{-\zeta_c' + \zeta_c} C_{cc'} (p_{opt})^{1/2} R^0_{cc'} \Gamma_{cc'} + i\phi_{c'}^{-1/2} e^{i\phi_R} \Gamma_{cc'}^{-1/2} \Gamma_{c'c}]^1/2
$$

where $c$ and $c'$ represent entrance and exit channel functions. The symbols have the following interpretation:

- $\zeta$ = the imaginary part of the optical phase shift
- $p_{opt}$ = the optical penetrability evaluated at the matching radius
- $R^0$ = the background $R$-matrix
- $\rho$ = the wave number times the matching radius
- $f, g$ = the regular and irregular optical wave functions evaluated at the matching radius
- $\phi_R$ = the resonance mixing phase
- $\Gamma_{cc'}$ = the partial width for resonance $\lambda$ to channel $c$
- $E_R$ = the resonance energy
- $\Gamma$ = the total width of resonance $\lambda$ which we take to be energy independent (not rigorously correct)

We can further interpret some of the above in terms of the reduced width $\gamma$ and the boundary condition number $B$:

$$
\Gamma_{cc'} = 2p_{cc'} e^{-2\zeta_c} \gamma_{cc'}^2 / (\sum_c (1 - \frac{3\Delta_{\lambda\lambda}}{\delta E} E_R))
$$

$$
\phi_R = \tan^{-1} \left( \frac{\text{Im} \, d_c}{\text{Re} \, d_c} \right)
$$
\[
\begin{align*}
p_{c}^{\text{opt}} &= \rho_{c} |d_{c}|^2 \\
d_{c} &= \frac{\text{df}_c}{\text{df}_c} - f_c R_c / \rho_c
\end{align*}
\]

The utility of Eqs. (1)-(5) depends on three tests. The first is that if \( R_0^{c'} \) is assumed real (not obviously required because the optical models used in the elastic channels describe only the gross structure of the elastic cross sections) then the relative phase between the resonance and the background should be correctly predicted. Second, although \( R_0^{c'} \) may be energy dependent, it must be slowly and smoothly varying or else the single level plus background assumption implied by Eq. (1) would be invalid. These two criteria are still under investigation, but preliminary results indicate these restrictions are not too severe.

The other is that by using Eq. (2) we get dimensionless reduced widths for all channels which are more energy independent. Figure 10.3-1 shows the factor \( P/R^2 \) as a function of the matching radius \( R \) under several different optical model assumptions. We show \( P/R^2 \) because it is the radially dependent factor in Eq. (2), where the \( 1/R^2 \) comes from the conversion to the dimensionless reduced width \( \delta^2 = \gamma^2/(4R^2/mR^2) \). Perfect success of the theory would be to have \( P/R^2 \) a horizontal line. The rapid variation when Coulomb wave functions are used is clearly seen. The two types of broken curves show the effects of including the inversion of the \( (1 - R^{0}_{10}) \) matrix. The two potentials \( A \) and \( B \) are derived from phenomenological fits to the elastic \( ^{12}\text{C} + ^{12}\text{C} \) elastic scattering data.

Figure 10.3-1 shows that the theory is not a very good solution to the problem, even though there is some fairly slowly varying region outside the radius parameter of the potentials \( R_0 \).

Fig. 10.3-1. \( P/R^2 \) is the radially dependent factor which corrects the dimensionless reduced width to the observed partial width. The drawing shows the radial dependence of this factor calculated with Coulomb wave functions and two different sets of optical wave functions. The two types of broken curves show the importance of corrections due to the inversion of the \( (1 - R^{0}_{10}) \) matrix. \( R_0 \) is the radius parameter of the optical potentials \( A \) and \( B \).
Clearly, the theory has also introduced a strong dependence on the optical potential.

The remaining hope, which is still to be tried, is to remove the optical model dependence by evaluating each penetrability at a radius equal to the radius of an equivalent square well for the optical potential. Then, by using Eq. (2) with $K_0$ equal to the shift function at resonance, we can calculate $\delta^2$ and divide it by the $G_0^2$ from the equivalent square well. Hopefully, this ratio will be less dependent on the optical potential and the relative channels will have their relative importance in the structure of the state measured by the size of this ratio. If these hopes are borne out, we will be able to answer some of our original questions about the quasi-molecular states.

1. Nuclear Physics Laboratory Annual Report, University of Washington (1973), p. 31

10.4 Search for Quasimolecular Resonances in the System $^{18}_0 + ^{12}_C$

R. Vandenbosch, M.P. Webb, and M.S. Zisman

Elastic scattering excitation functions for heavy ions in the mass 12 to mass 16 region are characterized by oscillatory structures of dissimilar origins. In addition to gross structure 2-3 MeV wide in the center of mass there is, in some instances, structure a few hundred kilovolts wide superimposed on it. High resolution measurements reveal structure several tens of kilovolts wide superimposed on the above two. The gross structure can be reproduced with a weakly absorbing optical model potential implying an unusually large transparency for the grazing partial waves. This may be attributed to angular momentum mismatch between the entrance and the reaction exit channels. The fine structure may be understood in terms of a statistical compound nucleus mechanism (Ericson fluctuations).

The origin of the intermediate structure is less clear. Intermediate structure in the elastic scattering of $^{12}_C + ^{12}_C$ near the Coulomb barrier is strongly cross correlated with the total $\rho$, $\sigma$, and $\gamma$ cross sections, precluding any possibility of these resonances being of a random, statistical origin. The concept of resonances in "molecular" potential wells was invoked to explain these results. Evidence for intermediate structure in elastic scattering well above the Coulomb barrier has only been seen in the $^{12}_C + ^{16}_O$ system.

This investigation was designed to learn more about the origins of intermediate structures and in particular to see if the $^{18}_0 + ^{12}_C$ system exhibits any evidence for quasimolecular resonances both at and above the Coulomb barrier. To this end we have initiated kinematic coincidence measurements of the elastic
scattering at 60° and 90° (c.m.). The $^{16}$O beam was obtained by introducing 50% enriched $^{18}$O water vapor into the direct extraction ion source. The targets were carbon foils 75-100 μg/cm² thick. Kinematic coincidence measurements were accomplished by using surface barrier detectors; the angle defining detectors subtended 0.4° (1ab) in the reaction plane while the recoil detectors subtended 3.5°. This choice of scattering angles also allows the measurement of the reaction channel $^{14}$C + $^{16}$O (both the α and the two neutron transfer) simultaneously with the elastic scattering. This will allow a check of the cross correlation of any resonances seen in the elastic scattering. An initial experiment has just been completed and the data are under analysis.


10.5 Entrance Channel Effects in the $^{32}$S System: Comparison of $^{12}$C + $^{20}$Ne and $^{16}$O + $^{16}$O Elastic Scattering

R. Vandenbosch, M.P. Webb, and M.S. Zisman

The dramatic structure exhibited in $^{16}$O + $^{16}$O elastic scattering¹ has been shown to be absent in $^{18}$O + $^{18}$O scattering,² demonstrating that such structure is not a universal feature of identical boson systems in this mass region. It has been suggested that the dissimilarity between the two systems is related to the inhibition of the direct reaction channels for $^{16}$O + $^{16}$O caused by angular momentum mismatching between the entrance and exit channels. This inhibition of the direct inelastic and transfer channels for $^{16}$O + $^{16}$O leads to a higher transparency for the grazing partial waves and hence to large, oscillatory elastic scattering cross sections. For $^{18}$O + $^{18}$O, however, such mismatches can be avoided due to more favorable Q-values. Alternate explanations for the observed differences have emphasized the role of the compound nuclear level densities or the number of open decay channels from the compound nucleus.

To further elucidate the important factors we have studied the $^{12}$C + $^{20}$Ne system, which leads to the same compound nucleus as $^{16}$O + $^{16}$O. Since the Q-values for the direct reaction channels in the former system are much more favorable, we expect considerably more absorption in the $^{12}$C + $^{20}$Ne entrance channel. Preliminary measurements taken with a conventional gas cell were found to be questionable as a check of an $^{16}$O + $^{16}$O elastic angular distribution taken with the same gas cell failed to exhibit the previously observed structure. This has been attributed to multiple scattering in the relatively thick metallic foil exit window. Therefore a new gas cell, described in Sec. 3.3 of this report, has been constructed.

Angular distributions for the $^{12}$C + $^{20}$Ne and $^{16}$O + $^{16}$O systems, taken under identical experimental conditions, are shown in Fig. 10.5-1. Other angular distributions for the $^{12}$C + $^{20}$Ne entrance channel are shown in Fig. 10.5-2.
Fig. 10.5-1. Elastic scattering angular distributions for $^{16}\text{O} + ^{16}\text{O}$ and for $^{12}\text{C} + ^{20}\text{Ne}$ at 23.3 MeV c.m.

The $^{12}\text{C} + ^{20}\text{Ne}$ system exhibits a very different behavior than $^{16}\text{O} + ^{16}\text{O}$, having an almost monotonically decreasing cross section which is lower in absolute magnitude. Comparison of the $^{12}\text{C} + ^{20}\text{Ne}$ angular distributions with those from the $^{16}\text{O} + ^{16}\text{O}$ system at bombarding energies spanning the energy required to match the compound nucleus excitation energies shows that the characteristic differences persist. Optical model calculations using the $^{16}\text{O} + ^{16}\text{O}$ potential but run for an assumed non-identical boson system and analogous calculations with a potential fitting the $^{12}\text{C} + ^{20}\text{Ne}$ scattering but run for an identical particle system demonstrate that the differences between the two systems are not simply a consequence of one of the systems consisting of identical bosons.

Further evidence for the difference in the absorption of the two systems is exhibited by comparison of the 70° (c.m.) excitation functions shown in Fig. 10.5-3. This angle was chosen to be far enough forward so that the differences between identical and non-identical particle systems would be small and yet far enough back so that considerable gross structure is exhibited by the $^{16}\text{O} + ^{16}\text{O}$ system. Again one sees that the $^{12}\text{C} + ^{20}\text{Ne}$ system exhibits a more damped excitation function characteristic of strong absorption.

We have also measured an angular distribution for inelastic scattering to the 1.63 MeV 2+ state of $^{20}\text{Ne}$. This measurement, shown in Fig. 10.5-4, displays considerable structure and a quite large absolute cross section. The latter
Fig. 10.5-3. The 70° c.m. excitation function for $^{12}$C + $^{20}$Ne elastic scattering is compared with that measured previously (Ref. 1) for $^{16}$O + $^{16}$O.

Fig. 10.5-4. Angular distribution for inelastic scattering to the 1.63 MeV 2+ state of $^{20}$Ne.

characteristic indicates that this excitation may be an important channel to be considered in the absorption effects of the entrance channel. Coupled channels calculations will be performed to explore this idea.

The compound nuclear angular momentum distributions for the two systems should be rather similar since the maximum $l$ values for which absorption occurs differ by less than one unit at the same compound nucleus excitation energy. Thus, our results imply that the prominent gross structure observed for $^{16}$O + $^{16}$O is not due to the level density or number of decay channels of the compound nucleus, but is rather an entrance channel effect.

10.6 The $^{12}\text{C}(1^\text{He}, 1^\text{H})^{13}\text{C}$ Reaction at 100 MeV

J.G. Cramer, R.M. DeVries, † K-L. Liu, M.S. Zisman, F.D. Becchetti, † †
B.G. Harvey, † † H. Homeyer, † † D.G. Kovar, † † J. Mahoney, † † and
W. von Oertzen † † †

Recently it has been shown that the inclusion of "recoil" in numerical
DWBA calculations of heavy ion transfer cross sections strongly affects the pre-
dicted differential cross sections in both shape and magnitude, particularly at
higher energies, and explains many observations which were not previously under-
stood. 1, 2 In particular, the inclusion of recoil increases the number of $\lambda$-trans-
fers which can contribute to the cross section. This can be seen from consider-
ing the selection rules. The angular momentum selection rules for a reaction
$A(a,b)B$ are:

$$|l_1 - l_2| \leq \lambda \leq l_1 + l_2$$

and

$$|j_1 - j_2| \leq \lambda \leq j_1 + j_2$$

where $a = b + x j_{1 \frac{1}{2}}$ and $B = A + x j_{2 \frac{1}{2}}$.

i.e., $b$ and $A$ are the cores between which $x$ is transferred.

If recoil effects are not included, there is an additional "rule" which
is an artifact of the "no-recoil" approximation. It is: $(-1)^\lambda = \Delta \pi$ where $\Delta \pi$ is
the change in parity from the initial to the final system. The $\lambda$-values which
satisfy this pseudo rule are called "normal" $\lambda$'s and those which do not are
called "non-normal" $\lambda$'s. The contributions of these non-normal $\lambda$-transfers to
the cross section have been found to be quite important in many heavy ion
reactions.

One example of this was the successful analysis of single nucleon transfer
reactions induced by $^{14}\text{N}$ on $^{12}\text{C}$ and $^{11}\text{B}$ at high energies. 1 The relative lack of
structure in some of the angular distributions for these reactions was explained
by the complementary contribution of a "normal" $\lambda = 0$ transfer and a "non-normal"
$\lambda = 1$ transfer, both of which were highly structured but out of phase with each
other. In particular, the $^{12}\text{C}(^{14}\text{N},^{13}\text{N})^{13}\text{C}(g.s.)$ reaction at 78 MeV was well fit
with the incoherent sum of these rapidly oscillating components, producing a
smooth angular distribution in reasonable agreement with the data.

This explanation of a relatively structureless angular distribution is
quite plausible, but it would be preferable to fit an angular distribution with
structure to test the correctness of the theoretical treatment. Such a test can
be achieved by measuring the angular distribution of the reaction $^{12}\text{C}(^{14}\text{N},^{13}\text{N})^{13}\text{C}$
(3.09 MeV, 2s1/2) which, according to the first of the above selection rules,
will have only an $\lambda = 1$ contribution to the cross section. If this contribution
has the same rapidly oscillating angular dependence found in the $\lambda = 1$ contribu-
tion to the $^{13}\text{C}$ ground state cross section, then the experimental 2s1/2 angular
distribution would be expected to have pronounced oscillations.

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Fig. 10.6-1. Position spectrum for the $^{12}\text{C}(^{14}\text{N},^{13}\text{N})^{13}\text{C}$ reaction.

To test this prediction, we have measured the $^{14}\text{N} + ^{12}\text{C}$ elastic scattering and single nucleon transfer differential cross sections at a bombarding energy of 100 MeV using a $^{14}\text{N}$ beam from the Berkeley 88" cyclotron. The reaction products were analyzed with a magnetic spectrometer system. A momentum spectrum for the transfer reaction is shown in Fig. 10.6-1, with the ground, 3.09 MeV, and 3.85 MeV states indicated. Since $^{13}\text{N}$ is bound by only 1.94 MeV, no excited states of $^{13}\text{N}$ are expected in the spectrum.

Figure 10.6-2 shows the angular distributions of the $^{13}\text{C}$ states. Also shown for comparison is the measured elastic scattering angular distribution and its optical model fit. It can be seen clearly from Fig. 10.6-2 that the $^{13}\text{C}$ ground state (1p1/2) does not oscillate while the angular distribution for the 3.09 MeV (2s1/2) state has pronounced oscillations, in qualitative agreement with the prediction given above. However, a serious discrepancy appears when the oscillations of the 3.09 MeV (2s1/2) angular distribution are compared with those of the elastic scattering angular distribution in Fig. 10.6-2. We see that the two distributions oscillate out of phase. The diffraction model for heavy ion transfer reactions indicates that this phasing is characteristic of an even $\ell$ transfer and, as has been previously mentioned, the transfer reaction is expected to populate the 2s1/2 state with $\ell = 1$ only. It is possible that the diffraction model is too crude to give reliable predictions of such phasing. To investigate this question we must employ a more accurate theoretical treatment.

Exact finite range DWBA calculations including recoil were made using the program LOLA. These are shown in Fig. 10.6-3. The ground state (1p1/2) angular distribution is reasonably well fit with the DWBA prediction which is an incoherent sum of $l = 0$ and $l = 1$ components and gives a product spectroscopic factor of 0.51. This number is in good agreement with the value determined in the 78 MeV analysis (0.53) and with the theoretical value of Cohen and Kurath (0.42). The 3.85 MeV (1d5/2) angular distribution is also well-reproduced by the DNEA calculation, although in this case the measured spectroscopic factor (0.37) is less than the expected value of unity. [Based on a comparison with high-resolution $^{12}\text{C}(^{6}\text{Li},^{6}\text{Li})$ data, the contribution to the 3.85 MeV peak from the unresolved 1p3/2 level at 3.64 MeV is expected to be small.] However, the $\ell = 1$ prediction for the 2s1/2 angular distribution is clearly out of phase with the data, as anticipated by the consideration of the diffraction model above.
Fig. 10.6-2. Experimentally observed angular distributions. The elastic scattering optical model fit was obtained with the parameter set: $V_0 = 145$ MeV, $r_0 = 0.925$ F, $a_0 = 0.816$ F, $W_{vol} = 35.3$ MeV, $r_T = 1.30$ F, $a_T = 0.178$ F, where $R = r_0 (12^{1/3} + 14^{1/3})$. The triangular points in the $^13C$ ground state angular distribution were obtained from measurements of the mirror reaction $^12C(^{14}N, ^13C)^13N$(g.s.). The solid curves through the transfer reaction angular distributions are only to guide the eye.

and the normalization shown in Fig. 10.6-3 yields a spectroscopic factor (0.25) considerably smaller than expected. Curiously, the data bear an amazing resemblance in phase and shape to the $l = 0$ contribution to the ground state angular distribution.

We have investigated the dependence of these predictions on the optical model parameters used. Other parameter sets which fit the $^{14}N + ^12C$ elastic scattering in this energy region were tried in the DWBA calculations. Also investigated were the effects of small changes in the bound state parameters (those used in the fits shown are $r_0 = 1.25$ F and $a = 0.65$ F). None of these changes produced any discernable change in the phase of the angular distributions.

Since the finite range DWBA program LOLA has given good agreement with other oscillating angular distributions in this mass and energy region (no $2s_{1/2}$ states were studied, however) and has also correctly predicted the angular distribution of a $2s_{1/2}$ state in the $^{30}Si(^{16}O, ^15N)^{31}P$ reaction at 42 MeV, we must conclude that the fault does not lie with the code, and that the reaction process responsible for the population of the $2s_{1/2}$ state is somehow not being correctly described.
In summary, we find that the ground and 3.85 MeV state angular distributions are well-reproduced by finite-range DWBA calculations but the 3.09 MeV state has a highly oscillatory angular distribution which is completely out of phase with the theoretical prediction. The explanation for this anomaly is presently unknown and further measurements should be undertaken to clarify the reaction mechanisms in this mass region.

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†† Collaborators from Lawrence Berkeley Laboratory.

Fig. 10.6-3. DWBA calculations (using the optical parameters of Fig. 10.6-2) for the $^{12}C$ ground, 3.09 MeV, and 3.85 MeV states. As discussed in the text, the 3.09 MeV excited state should be an $\ell = 1$ transfer but seems to more closely resemble an $\ell = 0$ transfer.
The Elastic Transfer Reaction $^{12}\text{C}(^{14}\text{N},^{14}\text{N})^{12}\text{C}$

Y-D Chan, J.S. Cramer, B. Cuengco, K-L Liu, and M.S. Zisman

An experiment has been carried out to measure the elastic scattering angular distribution for the reaction $^{12}\text{C}(^{14}\text{N},^{14}\text{N})^{12}\text{C}$ at a lab energy of 33 MeV.

It is well recognized that the interference of the $Q = 0$ transfer amplitude produces significant backward angle oscillations in the angular distribution for systems with almost identical target and projectile nuclei. This mechanism has been studied experimentally most extensively in the case of single nucleon transfer. Satisfactory fits in most cases were obtained either in the LCNOL method or from DWBA-type calculations. However, experimental data for the elastic transfer of two nucleons are comparatively rare, even though there exist some data in the case of two-neutron transfer. In our case, it is assumed that the oscillations are due to the transfer of a deuteron-like cluster.

A $\Delta E$-E telescope made up of surface barrier detectors was used to measure the angular distribution. The thickness of the $\Delta E$ detector was about 9.8 $\mu$ and the E detector was about 70 $\mu$. A data collection program with particle identification was used to distinguish between the $^{14}\text{N}$ and $^{12}\text{C}$ particles.

The $\Delta E$ detector stopped $^{14}\text{N}$ particles of about 13 MeV and $^{12}\text{C}$ particles of about 10 MeV. The bombarding energy (33 MeV in the lab system) was chosen to just cover the whole angular range we are interested in. The telescope was mounted on an In-Out device so that we could take data at angles as small as 5° (lab).

So far, we have been able to get only very preliminary data. The enhanced cross section at backward angles does support the presence of an interference mechanism, but the data are too crude to indicate any detailed structure of the oscillations. To see that these elementary data really make sense, we have attempted to fit them with a DWBA calculation.

Formally we can describe the interference mechanism as:

$$T_{\text{tot}}(\theta) = T_{\text{elastic}}(\theta) + \alpha T_{\text{transf}}(\pi - \theta)$$

(1)

where $\alpha$ is a constant which depends on the statistics of the identical cores. Its explicit form can be worked out theoretically. In our case it is considered as a parameter in fitting the angular distribution. The optical parameter search code GENOA was used to get the optical model parameters by fitting the data up to 77° in the center of mass system. These parameters were then used to estimate the transfer amplitude by the full-recoil DWBA code LOLA. The result with the value of $\alpha$ is shown in Fig. 10.7-1.

Finer measurements at different energies will be carried out to get more information about the mechanism.
7. R. Vandenbosch, to be published.
8. See Sec. 4.2 of this report.

10.8 Heavy Ion Elastic Scattering from sd-Shell Nuclei


We have continued the detailed study of elastic scattering of $^{16}_0$ by $^{28}_1$Si. This work is aimed at obtaining a body of data which spans a significant range of bombarding energies, includes measured cross sections down to $10^{-4}$ of the Rutherford cross section, and is measured in sufficiently small angular steps (1.1°) to reveal the presence of diffraction-type oscillations in the cross section. We have expanded our study to include other targets (27Al, 25Mg) and other projectiles (14N, 17O, 19F) and have added to the data set some data from other laboratories.

Table 10.8-1 summarizes the data set.

A problem was encountered in attempting to use data from Argonne measured by Siemsen et al. for 55 MeV $^{16}_0 + ^{28}_1$Si. Their data showed pronounced oscillations which proved to be highly resistant to optical model analysis. A re-measurement of the 55 MeV elastic cross section at this Laboratory showed a significantly different overall shape and proved to be much more tractable to optical model analysis. It is believed that the kinematic coincidence technique used by the Argonne group is responsible for the discrepancy.

A modified version of the global optical model search code GENOA written by F. Perey has been used in an attempt to find an energy independent 4-parameter
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(V, W, r₀, and a) potential which will give fits to the complete data set. (r₀ = r₀(A₁²⁺ + A₂²⁺)). This attempt has only been partially successful. Potential I given in Table 10.8-2 gives good fits to the low and high energy data, but fails to reproduce the oscillations observed in the medium energy 50-60 MeV data. Potential II, which is a rather peculiar 6-parameter potential aimed specifically at reproducing the medium energy oscillations does not give a completely satisfactory fit to the low (33-40 MeV) and high (72-81 MeV) energy data, failing to reproduce the slope of the low energy data and predicting pronounced oscillations in the high energy region where the data appear to be relatively smooth. Figure 10.8-1 illustrates the fits which these two potentials give to several of the data sets.

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<th>r₀</th>
<th>a₀</th>
<th>t₀</th>
<th>W</th>
<th>r₁</th>
<th>a₁</th>
<th>t₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>100</td>
<td>1.06</td>
<td>.640</td>
<td>13.806</td>
<td>42</td>
<td>1.06</td>
<td>.640</td>
<td>12.990</td>
</tr>
<tr>
<td>II</td>
<td>100</td>
<td>1.194</td>
<td>.508</td>
<td>17.563</td>
<td>374.2</td>
<td>.839</td>
<td>.167</td>
<td>33.986</td>
</tr>
</tbody>
</table>

\[ t₀ = \ln V + \frac{r₀}{a₀} \]
\[ t₁ = \ln W + \frac{r₁}{a₁} \]

The potentials here are not unique and were arbitrarily chosen such that V = 100 MeV. Any potential which predicts the tail region correctly is found to give essentially the same scattering due to the well known Igo ambiguity.⁴ We have investigated the extent of this ambiguity for Potential I, and the results are shown in Fig. 10.8-2. A set of 4-parameter potentials such that \( t₀ = \ln V + \frac{r₀}{a₀} = 13.806 \), \( a₀ = 0.640 \), and \( W/V = 0.442 \), which we have designated as Class I potentials, were generated and the \( \chi² \) values for various data sets were calculated and plotted against V. Figure 10.8-2a shows the potentials used and Fig. 10.8-2b shows the \( \chi² \) dependence. Class I potentials up to the GeV region were found to predict identical scattering, provided the tail behavior remains unchanged. Potentials which have less absorption in the tail region may be expected to have somewhat more complicated ambiguities because of the larger contributions from radial regions where V(r) becomes non-exponential.

The sensitivity of the calculations to various regions of the potential was investigated by calculating \( R_{\text{max}} \), the radius at which the external total potential has its maximum value for the partial waves of interest. This radius, calculated with the 100 MeV potential at various bombarding energies, is also shown in Fig. 10.8-2a. As shown, the range of energies used in this investigation would be expected to discriminate against potentials of 50 MeV or less, but would not be expected to discriminate between potentials with depths greater than 100 MeV.

In addition to the potentials given above, we have attempted to introduce \( \lambda \)-dependent and energy-dependent absorption to obtain improved fits to the data.
Fig. 10.8-1. $^{16}$O + $^{28}$Si elastic scattering data and fits with potentials I (solid line) and II (dashed curve). 33, 36, and 38 MeV data are taken from Ref. 5.

Fig. 10.8-2. (a) Class I potentials from $V=1$ MeV to $V=500$ GeV. Also shown are radii of maximum sensitivity calculated with the 100 MeV potential with $E_{\text{lab}} = 27$ to 150 MeV. (b) $\chi^2$ values for fits to three data sets with various Class I potentials.
Thus far, these attempts have not resulted in significantly improved fits. The
difficulty seems to be that any potential which predicts the medium energy
oscillations will predict even larger oscillations at the higher energies, in
disagreement with the data. Work is continuing in an attempt to find a satis-
factory solution to this dilemma.

1. Nuclear Physics Laboratory Annual Report, University of Washington (1973),
   Sec. 11.5.
2. R.H. Siemssen, ANL-7837, p. 145 (1971); C.0. Greenwald, A. Richter,
7. J. Ball et al., in Symposium on Heavy Ion Transfer Reactions, PHY-1973B,

10.9

\[ \text{16,18}_0 \text{ Elastic Scattering from } ^{58}\text{Ni} \]

Y-d. Chan, J.G. Cramer, B. Cuengco, R.M. DeVries, K-L Liu, and
M.S. Zisman

There has been much interest recently in the "anomalous" angular distribu-
tions which sometimes occur in heavy ion transfer reaction data.\(^{1-4}\) These dis-
tributions are anomalous because they are oscillatory and forward-peaked, as
opposed to the relatively structureless ball-shaped angular distributions typi-
cally seen in heavy ion reactions, even at energies well above the Coulomb
barrier.\(^{5}\) It has been demonstrated, in at least one case,\(^{2-6}\) that it is possible
to reproduce this forward peaking by means of DWBA calculations, providing a
weakly absorbing optical potential is employed. Since the weak absorption appears
consistent with the observed\(^{1,2}\) elastic scattering at forward angles, the explana-
tion seems reasonable. [Here and in what follows we define "forward angles" as
angles where \(\sigma/\sigma_R \approx 10^{-2}\) and "backward angles" as those where \(\sigma/\sigma_R \approx 10^{-2}\).]

However, such weak absorption does lead to some conceptual problems since, for
example, it corresponds to an exceedingly long mean free path for the heavy
ions.\(^{7}\)

In previous studies of heavy ion elastic scattering on sd-shell nuclei
undertaken at this laboratory,\(^{8}\) we found that a weakly absorbing potential tends
to predict too much structure in the back angle cross sections. Thus, it seemed
worthwhile to carefully study the elastic scattering of \(^{150}\) and \(^{180}\) from \(^{58}\text{Ni}\)
in order to extend the data to more backward angles. In this way it should be
possible to distinguish experimentally between strongly and weakly absorbing
optical potentials in this mass and energy region. To this end we have measured
the elastic scattering of \(^{180} + ^{58}\text{Ni}\) at \(E_\gamma = 63.4\) MeV and \(^{160} + ^{58}\text{Ni}\) at \(E_\gamma = 63,
71.5, \text{ and } 81\) MeV using an array of 8 large area rectangular Si(Li) detectors.
The data were taken in \(1.1^\circ\) steps to scattering angles such that \(\sigma/\sigma_R \approx 10^{-4}\).
The observed angular distributions are shown in Fig. 10.9-1. The \(^{180} + ^{58}\text{Ni}\)
data, which were obtained at 63.4 MeV in order to directly compare with the
Brookhaven results,\(^1\) show good agreement at forward angles, but drop off
more quickly at backward angles than do their data. The reason for this discrepancy is not presently understood.

The dashed curves in Fig. 10.9-1 are predictions of the weakly absorbing "Brookhaven" potential (Potential I in Table 10.9-1). As can be seen, this potential does a reasonable job of reproducing the forward angle data at all energies, but fails rather badly at backward angles. This is most obvious for the 81 MeV $^{160}$O data where the weak absorption introduces oscillations into the angular distribution which are clearly not present experimentally, in agreement with our findings in the sd-shell.\textsuperscript{8}

The solid curves in Fig. 10.9-1 represent fits to the data obtained with a heavy ion version of the optical model code GENOA.\textsuperscript{9} The parameters used are listed in Table 10.9-1 for $^{180}$O (Potential II) and $^{160}$O (Potential III). [In all of the fits discussed here, the $^{180}$ potentials were obtained by simultaneously fitting data from all three energies. Furthermore, the real well depth of 70 MeV was fixed in all parameter searches.] Both 4-parameter and energy dependent potentials were also tried

![Fig. 10.9-1. Elastic scattering angular distributions for $^{180} + ^{58}$Ni at 63.4 MeV and $^{160} + ^{58}$Ni at 53, 71.5, and 81 MeV. The solid curves are fits with the indicated potentials for $^{180}$ and $^{160}$, respectively. The dashed curves are predictions of the optical potential from Ref. 1. (Potential I in Table 10.9-1.)](image)

---

**Table 10.9-1. Optical Potentials for $^{16,18}_{16}O + ^{58}_{58}$Ni Elastic Scattering**

<table>
<thead>
<tr>
<th>Set</th>
<th>$V$ (MeV)</th>
<th>$r_R$ (fm)</th>
<th>$a_R$ (fm)</th>
<th>$W$ (MeV)</th>
<th>$r_I$ (fm)</th>
<th>$a_I$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>70</td>
<td>1.31</td>
<td>0.4</td>
<td>8.0</td>
<td>1.31</td>
<td>0.4</td>
</tr>
<tr>
<td>II</td>
<td>70</td>
<td>1.33</td>
<td>0.38</td>
<td>149.0</td>
<td>1.33</td>
<td>0.20</td>
</tr>
<tr>
<td>III</td>
<td>70</td>
<td>1.18</td>
<td>0.57</td>
<td>82.1</td>
<td>1.13</td>
<td>0.39</td>
</tr>
<tr>
<td>IV</td>
<td>70</td>
<td>1.19</td>
<td>0.54</td>
<td>18.5</td>
<td>1.19</td>
<td>0.54</td>
</tr>
<tr>
<td>V</td>
<td>70</td>
<td>1.16</td>
<td>0.60</td>
<td>39.6</td>
<td>1.16</td>
<td>0.60</td>
</tr>
<tr>
<td>VI</td>
<td>70</td>
<td>1.19</td>
<td>0.54</td>
<td>42.5-0.46 $E_{cm}$</td>
<td>1.19</td>
<td>0.54</td>
</tr>
</tbody>
</table>

\textsuperscript{a)} $R = r(A_1^{1/3} + A_2^{1/3})$. 

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Fig. 10.9-2. Radial dependence of potentials I and II from Table 10.9-1. The real well is nearly the same for the two cases.

and parameters for some of these are included in Table 10.9-1.

In order to choose between these parameter sets we have repeated some of the DWBA calculations for the $^{58}\text{Ni}(^{18}\text{O},^{16}\text{O})$ reaction at 63.4 MeV. Fitting these data was what led to the use of a weakly absorbing potential in Ref. 1. We find, in agreement with their results, that a strongly absorbing potential of the usual type (4-parameter) does not predict the transfer reaction correctly, giving a "bump shaped" angular distribution as opposed to the observed forward peaking. However, a potential with a geometry such as that of set II or III in Table 10.9-1 (see Fig. 10.9-2) does appear to do a more reasonable job in the DWBA calculations. Figure 10.9-3 shows angular distributions calculated with the finite-range DWBA code LOLA to several choices of optical parameters. As can be seen, the use of an imaginary well which is more square than the real well leads to about the same angular distribution as that for a weakly absorbing potential, but the wiggles in the back angle region are removed. A potential of this type has been used recently by Henning et al. to calculate other "anomalous" angular distributions in the $^{48}\text{Ca}(^{18}\text{O},^{14}\text{C})$ reaction with excellent results.

Thus, it appears that an optical potential with a relatively weak absorption in the surface region probably is required to adequately describe both the
elastic scattering and transfer data in this mass and energy region. However, potentials such as used here (Potentials II and III) have the advantage over the 4-parameter Brookhaven potential that they give a reasonable description of the elastic scattering over a fairly wide energy range and also reduce the unreasonably large mean free path of the incident heavy ions.

† Present address: University of Rochester, Nuclear Structure Laboratory, Rochester, N.Y. 14627.


9. Optical model code GENOA, F.G. Perey (private communication).

10. Finite range DWBA code LOLA, R.M. DeVries (private communication).

10.10 Deformation Effects in the Elastic Scattering of $^{84}\text{Kr}$ from $^{208}\text{Pb}$, $^{194}\text{Pt}$, and $^{197}\text{Au}$

R. Vandenbosch, M.F. Webb, and T. Darrah Thomas†

An experiment has been initiated to search for deviations from Rutherford scattering due to the dynamic deformation of the nuclei in their mutual Coulomb field. When two high-Z nuclei are brought close together (but not close enough to feel nuclear interactions) they should deform in their mutual Coulomb potentials in such a way as to lower the overall Coulomb interaction potential. Estimates of the magnitude are in the range of 1 to 10%, with the latter value probably being incompatible with data already available. The Coulomb-induced deformation should also result in a higher effective barrier if it were not for the fact that as the barrier is approached dynamic effects associated with the nuclear potential will tend to operate in the opposite direction.

We are therefore undertaking a careful study of elastic scattering just below and at the Coulomb barrier. Since the effects are expected to be small, we are performing a careful comparative study between the closed shell nucleus
\[ ^{208}\text{Pb}, \text{ which should be quite stiff with respect to deformation, } \text{ and } \]^{194}\text{Pt} \text{ and } ^{197}\text{Au}, \text{ which are very soft with respect to deformation. A preliminary experiment with 500 MeV Kr from the Lawrence Berkeley Laboratory's Super-HILAC has just been completed, and analysis of these results is in progress.} \]

†

Department of Chemistry, Oregon State University, Corvallis, Oregon 97331.
11. PHOTON EMISSION FROM NUCLEAR STATES

11.1 Gamma Branching Ratios of the 12.71 and 16.11 MeV States in $^{12}$C

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

The gamma ray branching ratios of the 12.71 MeV $J^{π}, T = 1^{+}, 0$ and 16.11 MeV $J^{π}, T = 2^{+}, 1$ states of $^{12}$C were investigated using the $^{10}$B($^3$He, pγ) reaction. The data were taken with a setup identical to that used for the measurement of the line shape and overall efficiency of the 10"×10" NaI detector for 15.1 MeV gamma rays (see Sec. 11.2 of this report).

The γ-ray branching ratio of the 12.71 MeV state has been measured previously. The most precise published result is $Γ_{γ_0}/Γ = 0.024 ± 0.003$. We have remeasured this quantity because it plays a role in the interpretation of our results on the isospin forbidden proton decays of the lowest $T = 3/2$ level in $^{13}$N (see Sec. 5.3 of this report) and in understanding the isospin violating decays of the 15.1 MeV $T = 1$ state in $^{12}$C (see Ref. 2). Our preliminary results for this branching ratio are $Γ_{γ_0}/Γ = 0.0214 ± 0.002$.

The gamma ray branching ratio of the 16.11 MeV state was examined because of a minor controversy surrounding this state raised in Ref. 3. Our results have not yet been analyzed.


11.2 Search for Isospin-Violating Effects in γ-Decays of the Lowest $T = 3/2$ Levels in $^{13}$C and $^{13}$N

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

The comparison of γ-ray transitions from narrow $T = 3/2$ levels which are isospin mirrors provides an opportunity to test the fundamental selection rule that $ΔT = 0,±1$ for electromagnetic transitions. This selection rule depends on the fact that the electromagnetic current transforms like the charge under isospin, decomposing into isoscalar and isovector terms but containing no isotensor component. Thus it is possible to investigate experimentally a fundamental property of the electromagnetic interaction which is not well verified. There are two ways in which this can be done. One is to look for gamma ray transitions between levels which differ by two units in isospin. The rate of such transitions is proportional to the square of the $ΔT = 2$ amplitude. An experiment of this kind is discussed in Sec. 11.3. Another way to test the selection rule is to compare corresponding $ΔT = 1$ transitions in mirror nuclei. Here the isoscalar interaction vanishes and one expects that the analogous decays will be identical in all respects.
This experiment compares the isospin allowed γ-ray transition strengths from the lowest \( T = 3/2 \) levels of \(^{13}\text{C}\) and \(^{13}\text{N}\) to the \( 1/2^- \) ground states and \( 3/2^- \) second excited states. These transitions are illustrated in Fig. 11.2-1. Mass 13 is an especially good case for this sort of comparison both because much is known about the isospin purity of \(^{13}\text{C}\) and \(^{13}\text{N}\) and because the isovector M1 transitions involved are strong and of high energy, which is experimentally advantageous. Since any difference in the transition strengths is expected to be small, a measurement of high precision is required. For this reason we have used identical geometry in obtaining the data for \(^{13}\text{C}\) and \(^{13}\text{N}\) and changed nothing in the γ-ray detection system between the two measurements.

The present experiment is similar to a previous measurement by Cocker et al., but benefits from a larger NaI detector of superior resolution, the calibration of the NaI detector at the same energy (15.1 MeV) as the ground state transitions in \(^{13}\text{C}\) and \(^{13}\text{N}\) using a separate coincidence measurement, and an event-by-event data handling system which allows singles and coincident proton spectra to accumulate simultaneously through the same ADC. Figure 11.2-2 shows a diagram of the experimental arrangement. The reactions \(^{11}\text{Be}(^{3}\text{He},py)^{13}\text{C}\) and \(^{11}\text{Be}(^{3}\text{He},ny)^{13}\text{N}\) were used to populate the 15.1 MeV \( T = 3/2 \) levels in \(^{13}\text{C}\) and \(^{13}\text{N}\) and the deexcitation γ-rays were detected in coincidence with the protons or neutrons. The protons and neutrons were both detected at 0° in circular detectors to order to align the residual nuclei and simplify the angular correlations. Since the angular correlation of the deexcitation γ-rays is limited to zeroth and second order Legendre polynomials the γ-ray detector was placed at 125°, which is a zero of \( P_2 \).

For the \(^{13}\text{C}\) part of the experiment a 5.3 MeV \(^{3}\text{He}\) beam was stopped in foils of Ni and Al with a total thickness of approximately 15 mg/cm². The foils were sufficient to stop both the \(^{3}\text{He}\) beam and alpha particles produced in the target, but not the proton group corresponding to the 15.1 MeV \( T = 3/2 \) level in \(^{13}\text{C}\). A 200µ surface barrier detector was used to generate stop pulses for a TAC and its output was summed with the output from the 3 mm detector to obtain the proton energy spectrum. For the \(^{13}\text{N}\) part of the experiment the foils and proton telescope were moved away from 0° and a 7.0 MeV \(^{3}\text{He}\) beam was stopped in a small Ta
Fig. 11.2-2. Experimental apparatus. The neutron detector, which is mounted on a track, was placed at a distance of 35 cm from the target.

Faraday cup. Neutrons were detected in a 4 1/2"x1" NE102 plastic scintillator at a distance of 35 cm from the target. A self-supporting enriched $^{11}$B target of about 180 μg/cm$^2$ was used for both parts of the experiment.

The Nuclear Physics Laboratory XDS 930 computer was used in combination with a new data collection program to record the data event by event and display various spectra on-line. Each coincident event consisted of three parts. For the $^{13}$C data these were the proton energy, the TAC signal, and the γ-ray energy from the 10"x10" NaI crystal.Routing was used to store separately γ-ray signals accepted and rejected by the anti-coincidence shield. For the $^{15}$N data the three signals were the neutron time-of-flight (timed against the γ-ray signal), the slow energy signal from the neutron detector, and the γ-ray energy. Figure 11.2-3 shows a neutron time-of-flight spectrum obtained by sorting the event data tapes with a window that included only events with γ-ray energy greater than 9.5 MeV. The neutron group corresponding to the 15.1 MeV $T = 3/2$ level in $^{13}$N is the only group in coincidence with γ-rays of this energy.

During the $^{13}$N part of the experiment a monitor detector was placed at 40° and an SCA window was set on the isolated ground state proton group from the reaction $^{11}$Be$(^3$He,p)$^{13}$C(g.s.). The monitor was used to tie this experiment to another experiment which measured the proton decays of the $T = 3/2$ level in $^{13}$N. This permitted the γ-decay branches of the $T = 3/2$ level to be measured relative
Fig. 11.2-3. Neutron time-of-flight spectrum for the $^{11}$B($^3$He, nγ)$^{13}$N reaction. Only events with γ-ray signals greater than 9.5 MeV are included. When events with γ-ray signals of lower energy are included the $T = 3/2$ peak is much less pronounced. The solid line is only to guide the eye.

to the well determined ground state proton branch.

With the use of appropriate gating signals and the new data collection program it was possible to collect a singles proton spectrum simultaneously with the coincidence data through the same ADC. Since the same computer interrupt was used for both singles and coincidence events, the effects of dead time, beam instabilities, and other changes in the experiment were completely compensated for. Figure 11.2-4 shows the singles proton spectrum in the region of the $^{13}$C($^{3/2}$) group and the coincidence spectrum corresponding to γ-rays with energy greater than 9.5 MeV. Since the singles and coincidence proton spectra are matched channel for channel only the central region of the $T = 3/2$ peak was used to obtain the number of singles and coincident events and compute the γ-ray branching ratio for $^{13}$C.

The final γ-ray spectra for both $^{13}$C and $^{13}$N are shown together in Fig. 11.2-5. The rejected NaI spectra were used only to monitor the operation of the NaI detector and are not shown. A random contribution, which is negligible in the case of $^{13}$C and small in the case of $^{13}$N, has been subtracted. The solid lines are the result of a non-linear least squares fit to a γ-ray lineshape obtained in a separate coincidence experiment using the reaction $^{10}$B($^3$He, pγ)$^{12}$C (15.11). The $^{12}$C(15.11) experiment was done together with the $^{13}$C-$^{13}$N measurement using the same experimental arrangement. Since the ground state γ-decay branch of the 15.11 MeV level in $^{12}$C is accurately known and nearly 100%, this
Fig. 11.2-5. γ-ray spectra corresponding to decay of the T = 3/2 levels in \(^{13}\text{C}\) and \(^{13}\text{N}\). Background due to random coincidences has been subtracted. The solid lines are least squares fits using the line shape obtained in the \(^{10}\text{Be}\,(\text{^3}\text{He},\gamma)^{12}\text{C}\) measurement. The dashed lines show the tails of the higher energy γ-rays.

measurement was also used to determine the product of efficiency and solid angle for the NaI detector at 15.1 MeV. For this reaction the angular correlation must also have the form \(a_0P_0+a_2P_2\). Figure 11.2-6 shows the γ-ray spectrum corresponding to the decay of the 15.1 MeV level in \(^{12}\text{C}\). The solid line is the empirically determined line shape at 15.1 MeV.

To fit the γ-rays of lower energy (\(γ_1\) and \(γ_2 + γ_3\)) the general form of the line shape was kept constant and its horizontal dimension was scaled in proportion to the γ-ray energy. During the fitting procedure the positions of the peaks corresponding to the transitions to the 1/2\(^{+}\) first excited states in \(^{13}\text{C}\) and \(^{13}\text{N}\) were fixed at their known energies. Although the transition to the 3/2\(^{+}\) second excited state is expected to go predominantly to that state rather than to the nearby 5/2\(^{+}\) level, it is not possible to resolve the two transitions in \(^{13}\text{N}\). In \(^{13}\text{C}\) the 170 keV separation of the 3/2\(^{−}\) and 5/2\(^{+}\) levels makes it possible to determine that the decay goes mostly to the 3/2\(^{−}\) level with an upper limit of 20% on the amount which could go to the 5/2\(^{+}\) level.

In Table 11.2-1 we display the absolute ground state γ-ray branching ratios for the lowest T = 3/2 levels of \(^{13}\text{N}\) and \(^{13}\text{C}\). These branching ratios in conjunction with previously known quantities give values for the total widths of the T = 3/2 levels \(Γ(^{13}\text{N})=0.77\pm0.15\) keV, \(Γ(^{13}\text{C})=5.80\pm0.69\) keV. This latter value is now in good agreement with a measurement obtained from the \(^{9}\text{Be}(α,γ_0)\)

Fig. 11.2-6. γ-ray spectrum from the 15.11 MeV level in \(^{12}\text{C}\) obtained in a manner similar to that used to obtain the \(^{13}\text{C}(T=3/2)\) data. A small peak, corresponding to the 2% branch to the 4.44 MeV level of \(^{12}\text{C}\), is just barely visible at 10.67 MeV. The solid curve is the line shape used in fitting all of the γ-ray spectra.
In Table 11.2-2 the relative γ-ray branching ratios for transitions to low lying states in $^{13}$C and $^{13}$N are presented. The reduced transition strengths are given in Weisskopf units in Table 11.2-3 and are based on previous measurements of $\gamma_0$ for $^{13}$C and $^{13}$N.5,7

Table 11.2-1. Ground state branching ratios for the lowest T = 3/2 levels of $^{13}$C and $^{13}$N.

<table>
<thead>
<tr>
<th></th>
<th>This Experiment</th>
<th>Ref. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\gamma_0}/\Gamma_{^{13}C}$</td>
<td>(0.414 ± 0.03)$%$</td>
<td>(0.53 ± 0.06)$%$</td>
</tr>
<tr>
<td>$\Gamma_{\gamma_0}/\Gamma_{^{13}N}$</td>
<td>(12.9 ± 1.2)$%$</td>
<td>(12 ± 2)$%$</td>
</tr>
</tbody>
</table>

Table 11.2-2. Relative branching ratios for decay of the T = 3/2 levels in $^{13}$C and $^{13}$N.

<table>
<thead>
<tr>
<th></th>
<th>$^{13}$C</th>
<th>$^{13}$N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\Gamma_{\gamma_2} + \Gamma_{\gamma_3})/\Gamma_{\gamma_0}$</td>
<td>0.770 ± 0.049</td>
<td>0.824 ± 0.061</td>
</tr>
<tr>
<td>$\Gamma_{\gamma_1}/\Gamma_{\gamma_0}$</td>
<td>0.191 ± 0.026</td>
<td>0.138 ± 0.032</td>
</tr>
</tbody>
</table>

Table 11.2-3. Comparison of reduced transition strengths (Weisskopf Units)

<table>
<thead>
<tr>
<th></th>
<th>$^{13}$C</th>
<th>$^{13}$N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_0$</td>
<td>0.33 ± 0.04$^*$</td>
<td>0.33 ± 0.05$^+$</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>$(6.9 ± 1.2) \times 10^{-3}$</td>
<td>$(4.2 ± 1.2) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\gamma_2 + \gamma_3$</td>
<td>0.58 ± 0.07</td>
<td>0.60 ± 0.1</td>
</tr>
</tbody>
</table>

$^*$ Derived from Ref. 7.
$^+$ Derived from Ref. 5.
The most precise comparison of all comes from the ratio

\[
R = \frac{B(Y_2 + B)}{B(Y_0)}
\]

which was found to be \(1.77 \pm 0.11\) for \(^{13}\text{C}\) and \(1.83 \pm 0.14\) for \(^{13}\text{N}\). Even the uncertainty in the difference of the NaI efficiency at the energies of \(Y_0\) and \(Y_2\) cancels in a comparison of these two numbers. If these results are interpreted in terms of an isotensor electromagnetic amplitude then the reduced transition strength \(B \approx \frac{1}{2}(1/2 \pm 1/2)A_1 + A_2|3/2 \pm 1/2|^2\) where \(A_1\) and \(A_2\) are the reduced isovector and isotensor electromagnetic amplitudes. Since the relative phase of \(A_2\) and \(A_1\) for the \(Y_0\) and \(Y_2\) transitions is not known it is possible that an unlucky combination of phases and amplitudes would suppress the effect of an \(A_2\) term in our experiment. On the other hand, our measurement becomes most sensitive to the presence of an isotensor amplitude for the case in which the ratio \(A_2/A_1\) has one sign for the ground state transition and the opposite sign for the excited state transition.

In particular, if \(\frac{A_2(Y_0)}{A_1} = + \frac{A_2(Y_2)}{A_1}\) then \(\frac{R(\text{C})}{R(\text{N})} = 1\), but if

\[
\frac{A_2(Y_0)}{A_1} = - \frac{A_2(Y_2)}{A_1} \quad \text{(and for } |A_2| \ll |A_1| \text{) then } \frac{R(\text{C})}{R(\text{N})} = 1 - 8 \sqrt{\frac{5}{3}} \frac{A_2}{A_1}.
\]

In the latter case our results would imply a one standard error limit of 2.1\% for the ratio of isotensor to isovector amplitudes \(A_2/A_1\).

3. See Sec. 4.8 of this report.
4. See Sec. 5.3 of this report.

### 11.3 Absolute Measurement of the Radiative Width of the Lowest \(T = 3/2\) Level in \(^{13}\text{N}\)

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

As discussed in Sec. 11.2 of this report, one may test the fundamental selection rule for \(\gamma\)-decay, \(\Delta T = 0, \pm 1\), by looking for differences in the strength of mirror \(\Delta T = 1\) \(\gamma\)-transitions. The mass-13 multiplet discussed previously provides a good opportunity to test not only the equality of relative decay strengths,
but also of absolute decay strengths. In $^{13}\text{C}$ the decay strength of the lowest $T = 3/2$ level to the ground state is known from inelastic electron scattering\(^1\) to be $\Gamma_\gamma = 23.3 \pm 2.6$ eV. In $^{13}\text{N}$ the absolute decay strength for the mirror decay is known to be $\Gamma_\gamma = 23.3 \pm 3.6$ eV from a combination of 2 separate measurements: 1) The absolute strength $\Gamma_\gamma \Gamma_\gamma / \Gamma = 5.5 \pm 0.8$ eV obtained from a measurement\(^2\) of the $^{12}\text{C}(p,\gamma_0)^{13}\text{N}$ resonance yield, and 2) the branching ratio\(^3\) $\Gamma_{p0}/\Gamma = 0.236 \pm 0.012$ for the lowest $T = 3/2$ level.

Of these 3 measurements, the least precise is the $^{12}\text{C}(p,\gamma_0)^{13}\text{N}$ resonance yield, which we have measured. The present measurements were done at $\theta_\gamma = 125^\circ$ using a 1.8 mg/cm\(^2\) natural carbon target. The measured yield curves show evidence for a small (5-10%) overshoot on the leading edge of the thick target resonance yield curve which is being interpreted in terms of the Lewis effect.\(^4\) In order to precisely calibrate the efficiency-solid angle for the NaI detector we have measured in exactly the same geometry the $\gamma$-rays from the decay of the 15.1 MeV $1^+ \ T = 1$ level of $^{12}\text{C}$ in coincidence with protons populating this level in the $^{10}\text{B}(3\text{He},p)^{12}\text{C}(15.11$ MeV) reaction. This efficiency measurement was done immediately following the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ measurement with no mechanical or electronic changes in between. The target purity was measured using elastic proton scattering and the presence of impurities was found to be negligible. Analysis of the present results is currently under way; we hope to obtain at least a factor of 3 improvement over the previous measurement of the absolute resonance strength.


11.4 Search for $\Delta T = 2 \gamma$-Decays of the Two Lowest $T = 2$ States in $^{20}\text{Ne}$

E.C. Adelberger, M.D. Cooper, R.E. Marxs, and K.A. Snover

In addition to the comparison of mirror $\gamma$-ray transitions discussed in Sec. 11.2 of this report it is also possible to test the $\Delta T = 0, \pm 1$ electromagnetic selection rule by searching for the presence of $\gamma$-ray transitions which the selection rule forbids. The isospin forbidden $\gamma$-decay of the first two $T = 2$ levels in $^{20}\text{Ne}$ to the low lying $T = 0$ levels provides an especially good opportunity for such a test. Most previous tests of this type have been concerned with forbidden E2 transitions competing with allowed M1 transitions. In $^{20}\text{Ne}$ previous limits on $\Delta T = 2$ transition strengths exist only for the E2 and M1 transitions from the $2^+ \ T = 2$ level to the ground and first excited states and for the E2 transition from the $0^+ \ T = 2$ to the $2^+(1.63$ MeV) first excited state.\(^1\) The present work provides limits for dipole transitions which, because they are intrinsically faster than E2 transitions, are in principle more sensitive to the presence of a $\Delta T = 2$ amplitude. Figure 11.4-1 illustrates the transitions for which we have obtained limits.

The work reported here has developed from a similar study attempted in the case of $^{40}\text{Ca}$ and reported last year.\(^2\) The $^{40}\text{Ca}$ experiment had to be abandoned
when the $2^+$, $T=2$ level could not be identified through the $^{39}$K(p,$\gamma$)$^{40}$Ca reaction. Previous studies of both the $0^+$ and $2^+$, $T=2$ levels in $^{20}$Ne using the $^{19}$F(p,$\gamma$)$^{20}$Ne reaction$^{1,3}$ have greatly facilitated the present experiment.

The University of Washington 10"x10" NaI spectrometer was used to obtain $\gamma$-ray spectra at 90° for proton energies in the neighborhood of 4.09 MeV for the $0^+$, $T=2$ resonance and 5.88 MeV for the $2^+$, $T=2$ resonance. The targets were $^6$LiF vacuum evaporated onto gold backings in a layer about 6 keV thick to the incident protons. An excitation function with 1000 $\mu$Coul of integrated beam at each energy was obtained across the $2^+$, $T=2$ resonance. Figure 11.4-2 displays the resulting $\gamma$-ray yields as a function of proton energy. The plotted points were obtained from windows set on the $\gamma$-ray spectra at the indicated energies. The width of the windows was scaled in proportion to the $\gamma$-ray energy in order to match the resolution of the NaI detector. Typical spectra obtained on and off resonance are shown in Fig. 11.4-3.

The resonance in the yield of the 10.63 MeV $\gamma$-ray corresponds to the cascade decay through the 12.25 MeV $T=1$ level and is the signature of a $T=2$ resonance. The yield of this $\gamma$-ray, which was found to correspond to a radiative width of 0.3 eV in previous work$^1$ has been used to calibrate the present limits. The 3.91 MeV $\gamma$-ray corresponds to proton decay of the $T=2$ level to an excited state of $^{19}$F and was measured in a separate excitation function. The curves drawn through the remaining excitation functions represent a linear background plus the two standard error limit of a least squares fit to the data using a yield curve of the same shape as that drawn through the 10.63 MeV data points. The corresponding limits for the $\Delta T = 2$ radiative widths are given in Table 11.4-1. The errors given in the table are statistical only and do not include the error in the background.

For the $\gamma_0$ and $\gamma_1$ transitions the observed background corresponds almost entirely to a real non-resonant $\gamma$-ray yield and it is possible that interference

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Fig. 11.4-1. Level scheme of $^{20}$Ne illustrating the isospin forbidden transitions for which experimental limits have been obtained. The allowed isovector decays of the two $T=2$ levels are shown at the extreme right of the diagram.
Fig. 11.4-2. Resonance yields for possible γ-ray transitions associated with the
2+, T = 2 level of ²⁰Ne. The 10.63 MeV γ-ray corresponds to the allowed decay
and the 3.91 MeV γ-ray is associated with proton decay to an excited state of ¹⁹F.
The remaining transitions are isospin forbidden. For the forbidden transitions
the curves are the two standard error limits of a fit to the data using a reso-
nance shape taken from the curve drawn through the 10.63 MeV data. The error in
the background, taken to be the straight lines shown in the figure, was not in-
cluded in the fitting procedure.
Fig. 11.4-3. γ-ray spectra on the peak of the 2+, T = 2 resonance and below the resonance. The broken arrow shows the location of the allowed transition and the solid arrows indicate the forbidden transitions for which limits have been obtained.

Effects could slightly modify the limits obtained here. However, it is felt that the procedure used is a most conservative one. Our limits are also based on the assumption that the angular correlations of the different γ-rays are identical.

Data similar to that presented here for the 2+, T = 2 level of 20Ne has been obtained for the 0+, T = 2 level and is presently being analyzed. However, a useful limit can be obtained only for one E1 ΔT = 2 transition from the 0+ level.

The interpretation of these limits poses interesting questions.

Table 11.4-1. Upper limits for ΔT = 2 transitions from 20Ne(2+, T = 2).

<table>
<thead>
<tr>
<th>Final State</th>
<th>Eγ (MeV)</th>
<th>Weisskopf Estimate (eV)</th>
<th>Experimental Limit (W.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s., 0+</td>
<td>18.43</td>
<td>5.53 (E2)</td>
<td>1.4 x 10⁻³</td>
</tr>
<tr>
<td>1.63, 2+</td>
<td>16.80</td>
<td>98.2 (M1)</td>
<td>5.4 x 10⁻⁴</td>
</tr>
<tr>
<td>4.25, 4+</td>
<td>14.18</td>
<td>1.49 (E2)</td>
<td>2.9 x 10⁻²</td>
</tr>
<tr>
<td>4.97, 2⁻</td>
<td>13.46</td>
<td>1212 (E1)</td>
<td>5.1 x 10⁻⁵</td>
</tr>
<tr>
<td>5.52, 3⁻</td>
<td>12.81</td>
<td>1045 (E1)</td>
<td>6.6 x 10⁻⁵</td>
</tr>
<tr>
<td>5.79, 1⁻</td>
<td>12.64</td>
<td>1004 (E1)</td>
<td>5.8 x 10⁻⁵</td>
</tr>
<tr>
<td>7.17, 3⁻</td>
<td>11.26</td>
<td>710 (E1)</td>
<td>9.9 x 10⁻⁵</td>
</tr>
<tr>
<td>7.42, 2⁺</td>
<td>11.01</td>
<td>27.7 (M1)</td>
<td>3.7 x 10⁻³</td>
</tr>
</tbody>
</table>

* Ref. 1.
For instance, suppose one views the results as a limit on the isotensor electromagnetic current. Since the form of such a current in nuclei is not known, it is difficult to predict the enhancement or retardation of $\Delta T = 2$ transitions as is done for the isospin allowed transitions (e.g., the hindrance of $\Delta T = 1$ E1 transitions). However, it is unlikely that $\Delta T = 2$ transitions to all of the low lying states would be inhibited, or that isospin impurities in the $T = 2$ states could conspire to cancel a genuine $\Delta T = 2$ amplitude in every case. Thus the limits for the four E1 plus the two M1 and two E2 transitions from the $2^+$, $T = 2$ level become more significant when taken together.


11.5 An Attempt to Study the Gamma Decay of the Lowest $T = 2$ State in $^{16}$O

E.G. Adelberger, J.E. Bussoletti, R.E. Marrs, and K.A. Snover

At present nothing is known about the gamma-decays of the $T = 2$ levels of $^{16}$O. We attempted to measure the gamma decay of the lowest $T = 2$ level using the $^{15}$N(p,$\gamma\gamma$) resonance reaction. The $\gamma$-decays of the $0^+ T = 2$ state will most likely feed the $J^\pi = 1^-, 1$ and $1^{+}, 1$ levels at 13.09 and 16.22 MeV respectively. These levels are particle unstable. Therefore in this case one must detect low energy (9.6 and 6.5 MeV) primary gamma rays since there are no high energy secondary $\gamma$'s analogous to those used as signatures in previous studies of $\gamma$ decays of other $T = 2$ levels.

The $^{15}$N + p channel seemed very well suited for this measurement since the branching ratio $T^p_0/T = 0.25 \pm 0.06$ is large.\(^1\) We employed a cylindrical gas target with a length of 17 cm. The entrance and exit windows of the cell were 0.013 mm thick kapton foils. Gamma rays were detected in the 10''x10'' NaI spectrometer. Lead shielding was arranged so that the NaI crystal viewed only the central region of the gas cell. The experiment was unsuccessful because of an intense background of high energy ($E_\gamma \leq 10$ MeV) gamma rays resulting from the $^{15}$N(p,$\gamma$) reaction.


11.6 Gamma Branching Ratios of $T = 1$ States in $^{20}$Ne Populated in $^{19}$F($^3$He,d)

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

The $\gamma$-decay of the two lowest $T = 2$ levels in $^{20}$Ne proceeds as a cascade through $T = 1$ levels at 11.2 and 12.25 MeV. The $\gamma$-ray branching ratios for these $T = 1$ levels are therefore important not only for the information they yield about the $T = 1$ levels themselves but also because of the role they play in
determining the radiative width of the T = 2 levels. Since it is the second member of the γ-ray cascade, corresponding to the 11.2 MeV + g.s. or 12.25 MeV + 1.63 MeV transitions, which is observed in studies of the T = 2 levels of 20Ne, the branching ratios for the T = 1 levels enter directly as a multiplicative factor in the measured radiative widths of the T = 2 levels.

For these reasons we have attempted a coincidence measurement of the branching ratios for these T = 1 levels using the 19F(3He,dy)20Ne reaction. A 3He energy of 15.0 MeV was used and deuterons were detected at 0° in a manner similar to that described elsewhere in this report. The incident 3He beam was ranged out in a stack of Ta foils covering the 0° detectors. γ-rays were detected in the 10"x10" NaI spectrometer at several different angles.

The d group corresponding to the 11.2 MeV T = 1 level does not appear in our spectrum, which is consistent with the small spectroscopic factor known for one parent state in 20F. The d group corresponding to the 12.25 MeV level is present but not completely resolved from a contaminant group in the singles spectrum. However, the line shape for the d group corresponding to the 12.25 MeV level has been obtained from the coincidence data and used to extract an accurate singles yield.

The calculation of the γ branching ratio for the 12.25 MeV T = 1 level is now in progress.

1. See Sec. 11.4 of this report and references cited therein.
2. See Sec. 11.2 of this report.

11.7 Gamma Decay of Unbound States in 24Mg: Search for the 10+ Member of the Ground State Rotational Band

K.A. Snover, J.W. Tape, and M.S. Zisman

Many of the low lying states of 24Mg can be classified into "rotational bands" on the basis of their energy spacings, decay modes, and transition strengths. In particular, the ground state band (K = 0) is known to extend up to a spin 8 state at 13.21 MeV, and a K = 2 band built on the 2+ state at 4.24 MeV is known up to an 8+ state at 14.15 MeV.

The known properties (energy, B(E2)) of the members of the ground state band are equally well described by shell model calculations and rotational model predictions. In a similar situation in 20Ne, a difference in the two model predictions appeared only for the high spin states of the band, and a measurement of the B(E2, 8+ → 6+) in 20Ne seems to favor a shell model description of that nucleus. The energies and B(E2) values of the high spin members of the rotational bands in 24Mg are likely to be important in differentiating between model predictions there as well, and it is the goal of this experiment to at least locate a possible 10+ member of the K = 0 (or K = 2) band for additional study.
The usual method for locating a candidate state for a rotational band is to look for a level in the appropriate energy region which decays by gamma ray emission to the next state in the band. A $^{10}$($K = 0$) level in $^{24}$Mg should appear in the region between $\pm 18$–21 MeV. As can be seen from Fig. 11.7-1 states in this region of excitation are unbound to $\alpha$, $p$, and $n$ emission, increasing the difficulty of the experiment considerably. For such an unbound state any observable gamma decay at all indicates some kind of unusual structure. For example the $8^+$ $K = 0$ state at 13.21 MeV is unbound to $\alpha$ decay by nearly 4 MeV; however, its primary decay mode is by gamma emission to the $6^+$ $K = 0$ state with an $\alpha$ branch to $^{20}$Ne of less than 1%. If the $10^+$ state has a similar structure (as it should if both are members of the same band) gamma emission could still be an observable decay mode.

States in $^{24}$Mg were excited by the $^{12}$C($^{16}$O,$\alpha$)$^{24}$Mg reaction at laboratory energies in the region 45–58 MeV. This reaction is known to excite high spin states in $^{24}$Mg. At a center of mass energy of 19.71 MeV the reaction proceeds through a resonance in $^{28}$Si with $I = 14$, indicating that in this beam energy region sufficient amounts of angular momentum are brought in to allow population of a $10^+$ state.

The experiment was originally attempted using a gamma-gamma coincidence system utilizing a relatively high efficiency Ge(Li) detector (9.3%) and the 10"\times"10" NaI spectrometer. Data were event recorded with $\gamma_1, \gamma_2$ and coincidence time (TAC) information written on magnetic tape and sorted on line by the program TAPAL. It became clear after attempting to analyze these data that the gamma-gamma technique is not sensitive enough. There are too many gamma rays in coincidence with one another, leading to complicated spectra, and the Ge(Li) (which was needed for good resolution) is not efficient enough for high energy (5 MeV) gamma rays.

In order to increase the sensitivity of the experiment an $\alpha-\gamma$ coincidence system was set up. Alpha particles with energies corresponding to excitation of the region of interest in $^{24}$Mg were detected at 0° by a simple telescope consisting of a 100 $\mu$ "delta E" and 700$\mu$ "E" totally depleted detectors followed by a 100$\mu$ "yeto" detector. A 19.3 mg/cm$^2$ Cu foil stopped the incident beam. (Cu can withstand higher beam currents than the Ni foils generally used.) A lower level discriminator on the delta signal removed all particles of charge 1 and high energy $\alpha$'s corresponding to excitation of low lying states in $^{24}$Mg. The

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**Partial Energy Level Diagram for $^{24}$Mg**

20.00

\[ \begin{align*}
4.97 & \quad 2^- \\
4.25 & \quad 4^+ \\
1.64 & \quad 2^+
\end{align*} \]

\[ \begin{align*}
14.15 & \quad 8^+ K=2 \\
13.21 & \quad 8^+ K=0 \\
0.331 & \quad 0^+ \\
9.53 & \quad 6^+ K=2 \\
6.11 & \quad 6^+ K=0 \\
0.331 & \quad 0^+
\end{align*} \]

\[ \begin{align*}
1.37 & \quad 2^+ K=0 \\
4.24 & \quad 2^+ K=2 \\
4.12 & \quad 4^+ K=0 \\
0.371 & \quad 0^+ K=0 \\
16.553 & \quad \frac{23}{23}Mg + n
\end{align*} \]

\[ \begin{align*}
11.693 & \quad \frac{23}{23}Na + p \\
6.67 & \quad \frac{16}{16}O + \frac{12}{12}C - \alpha
\end{align*} \]

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**Figure 11.7-1.**
delta and E signals were summed and sent to the computer along with gamma ray spectra from the 10"x10" NaI system. The coincidence TAC signals were derived from the delta signal, using constant fraction techniques, and the NaI signal. The (E_\alpha, E_\gamma, TAC) coincidence data were event recorded on magnetic tape and also sorted in a preliminary fashion on-line.

The signature of the gamma decay of the 10^+ state is an \alpha particle group in the proper excitation energy region (\sim 18-21 MeV) in coincidence with gamma rays from the de-excitation of the ground state band (E(8 \rightarrow 6) = 5.1 MeV, E(6 \rightarrow 4) = 4.0 MeV, E(4 \rightarrow 2) = 2.75 MeV, E(2 \rightarrow 0) = 1.37 MeV) as well as a gamma ray corresponding to the 10 \rightarrow 8 transition. To date a preliminary scan of data at beam energies of 46, 48, and 58.3 MeV has been completed with negative results for the 10^+ state. Some alpha groups at the proper energy are associated with gamma rays, however, the \gamma-ray energies are not consistent with the expected 10^+ decay scheme. These states are being investigated as they are interesting in their own right. Care must be taken not to confuse (\alpha,\gamma) coincidences from \isotope[24]{Mg} with (\alpha,\gamma) coincidences due to \alpha's exciting \isotope[24]{Mg} states which then particle decay to excited states which gamma decay. The analysis done so far has been with the spectra compressed (poor resolution) in order to do a rapid survey. In the future interesting regions will be rescanned at higher resolution where the \isotope[20]{Ne}, \isotope[23]{Na}, and \isotope[23]{Mg}, etc., gamma rays should be more easily distinguishable from the \isotope[24]{Mg} gammas. A more careful analysis may also turn up evidence for a very weak 10^+ gamma decay.

12. RADIATIVE CAPTURE

12.1 The $^{11}\text{B}(p,\gamma)^{12}\text{C}$ Reaction to Excited States of $^{12}\text{C}$

P. Paul and K.A. Snover

The present measurements of $^{11}\text{B}(p,\gamma)^{12}\text{C}$ from $E_p = 18$ to 23 MeV were designed to supplement more detailed measurements taken at Stony Brook below 16 MeV. The motivation behind this work is the study of radiative capture to excited states in the Giant-Dipole Resonance region. For completeness we discuss below some general observations based primarily on the data below $E_p = 18$ MeV.

Although the $(p,\gamma)$ reaction affords the unique possibility of studying the photonuclear properties of excited states of nuclei, in practice such studies have been restricted for the most part to transitions to the ground state and the first excited state. The study of transitions to excited states is interesting in that it may provide information both on the structure of these states as well as their coupling to the GDR.

The coupling of the $2^+$ quadrupole vibration to the $1^-$ GDR has been a subject of recent interest, and numerous calculations have been made of the effect of such a coupling on the GDR built on the ground state of various even A nuclei. Little theoretical attention has been given to the related question of the nature of the GDR strength built on (first) excited $2^+$ states. Although, in general, physical $2^+$ first excited states are not necessarily by any means purely vibrational in character, measurements in the GDR region of $(p,\gamma)$ reactions populating $2^+$ first excited states should in principle lead to information on such coupling. In light nuclei where experimental data are available, the situation is uncertain -- no clear-cut pattern has developed in the comparison of $(p,\gamma)$ measurements to $0^+$ ground states and $2^+$ first-excited states. In particular, previous measurements of the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction to the $2^+$ ground state and $2^+$ first excited state have shown a centroid energy for the $(p,\gamma_1)$ reaction which is displaced upward in energy compared to the ground state $(p,\gamma_0)$ reaction by roughly the energy of the first-excited $2^+$ state (4.4 MeV), a feature which may be taken as indicating weak coupling between the $0^+ \rightarrow 2^+$ and $0^+ \rightarrow 1^-$ excitations. Even so, a comparison of these 2 excitation curves shows some structure which may be correlated in energy, and these measurements have, in fact, been interpreted in terms of such a dipole-quadrupole coupling.

In this light, then, we felt it of interest to investigate the GDR built on other excited states with collective properties. The nucleus $^{12}\text{C}$ offers nearly unique opportunities for such measurements, and the $3^-$ "collective octupole" state at 9.64 MeV and the deformed second $0^+$ level at 7.65 MeV are of particular interest. In this paper we report measurements of the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction to the $0^+$ ground state and to the excited $2^+$, $0_2^+$ and $3^-$ states at 4.43, 7.65 and 9.64 MeV, respectively; the results are shown in Fig. 12.1-1.

The dominant feature of the $(p,\gamma)$ strength to the second $0^+$ level is its weakness relative to the other yield curves, especially relative to the yield

*See also Sections 17.9 and 17.10.
Fig. 12.1-1. Yield curves for the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reactions populating the $0_1^+$ (0.0 MeV), $2^+$(4.43 MeV) $0_2^+$ (7.65 MeV) and $3^-$ (9.63 MeV) states of $^{12}\text{C}$. The data below $E_p = 18$ MeV are from Ref. 1, and the data above $E_p = 18$ MeV are from the present work.
curve based on the $0^+_1$ ground state. Two questions are of interest here -- to what extent are the $0^+_1$ and $0^+_2$ states mixtures of the same intrinsic configurations, and to what extent is the $1^-$ GDR built on the $0^+_1$ ground state mixed with the $1^-$ GDR built on the $0^+_2$ state. The $0^+_2$ deformed state has been described as an $a$-cluster state or, equivalently, as a shell-model state with a large 4-particle-4-hole (4p-4h) component relative to the predominantly 0p-0h $0^+_1$ ground state. The lack of any observable cross section ($< 1\%$) for the $(p,\gamma 2)$ reaction at the peak of the $(p,\gamma 0)$ excitation curve at $E_p = 7$ MeV should yield a rather stringent restriction on the amount of such common configurations admixed into both of the $0^+$ levels. Takigawa and Arima$^3$ have described these two $0^+$ states in terms of linear combinations of two intrinsic $a$-cluster configurations corresponding to predominantly 0p-0h and 4p-4h shell model configurations, and they find the mixing of these two configurations to be about 4% in intensity, with the $0^+_1$ state being mostly 0p-0h and the $0^+_2$ state mainly 4p-4h. If we assume that the 4p-4h configuration does not contribute to the E1 capture strength for the $^{11}B + p$ incoming channel (see below), then, including phase space factors, this would lead to a predicted $\gamma_2/\gamma_0$ branching ratio at the $\gamma_0$ peak of about $(4\%)/(15/22.6)^3 \sim 1.3\%$ which is in reasonable agreement with our upper limit of 1% quoted above. A more detailed comparison of this sort which includes the effect of 2p-2h admixtures would be worthwhile, as such admixtures may tend to cancel the effect of 0p-0h admixtures in the $0^+_2$ state.

The lack of any apparent correlation in the $(p,\gamma 0)$ and $(p,\gamma 2)$ yield curves indicates little mixing between the $1^-$ GDR's built upon the $0^+_1$ and $0^+_2$ states. The fact that the $(p,\gamma 0)$ strength is centered at an excitation energy which is higher than the center of the $(p,\gamma 0)$ strength by roughly the $0^+_2$ excitation energy supports the idea of weak coupling between the $0^+_1 + 1^-$ and $0^+_2 + 1^-$ excitations. Finally the relative weakness of the $(p,\gamma 2)$ cross section is undoubtedly related to the fact that the $1^-$ GDR built upon the $0^+_2$ level does not couple well to the incoming proton channel. This can be understood from a simple shell-model point of view in which the $0^+_2$ level is predominantly of 4p-4h character relative to the $0^+_1$ ground state -- then the $0^+_1 + 1^-$ GDR excitation (which is predominantly of lp-1h character) when coupled to the $0^+_1 + 0^+_2$ 4p-4h excitation will not lead to configurations which overlap with the $p + ^{11}B$ incoming channel.

This qualitative argument would suggest, in contrast to single nucleon emission, that multinucleon emission such as $^3\text{He}$ emission should not necessarily be less probable from the GDR built on the $0^+_2$ state than from the GDR built on the $0^+_1$ ground state, since both lp-1h and 3p-3h configurations can couple to the $^9\text{Be} + ^3\text{He}$ channel. In fact, recent measurements$^4$ of $^9\text{Be}(^3\text{He},\gamma)^{12}\text{C}$ in the GDR region indicate comparable cross sections for population of the $0^+_1$ and $0^+_2$ states.

Part of the motivation for extending the Stony Brook results to higher energy came from a comparison of the $^{11}B(p,\gamma 2)^{12}\text{C}$ and $^9\text{Be}(^3\text{He},\gamma)^{12}\text{C}$ results. The latter measurements from $E_{^3\text{He}} = 1$ to 11 MeV ($E_X = 27-35$ MeV) show distinct resonances at $E_X = 28.5$ and 37.5 MeV. While there is a maximum in the $^{11}B(p,\gamma 2)^{12}\text{C}$ cross section near $E_X = 28.5$ MeV, the new results show there is no strong resonance near the higher energy. In general the new data for $16 \leq E_p \leq 23$ MeV show no new structure in any of the four different reaction channels, indicating the main structure is contained at lower energies.
12.2 The $^{12}\text{C}(\alpha,\gamma)_0^{16}\text{O}$ Reaction

E.G. Adelberger, D.R. Brown, and K.A. Snover

The work reported here represents a continuation of work reported last year (1973 Annual Report, p.111). The yield curve and angular distribution measurements have been completed over the range $E_\alpha = 7.0$ to 27.5 MeV, and the differential cross section has been decomposed into its E1 and E2 components, shown in Fig. 12.2-1 along with the relative phase factor $\cos \delta$.

The region between $E_\alpha = 7 \text{ and } 9$ MeV has been studied in some detail in order to resolve a long-standing problem concerning the parameters of a $2^+$ resonance which falls underneath a very strong $1^-$ resonance. The results are shown in Fig. 12.2-2. The differential cross section is dominated by the E1 resonances (see Ref. 1) and the results here for $\sigma_{E1}$ and $\sigma_{E2}$ were obtained by decomposing 3- and 4-point angular distributions at each energy. The E2 cross section is shown in more detail in Fig. 12.2-3. The quantity plotted on the abscissa is $E_\alpha - 1/2 \Delta E_t$ where $E_\alpha$ is the bombarding energy and $\Delta E_t$ is the beam energy loss in the target ($\Delta E_t \approx 240 \text{ keV at } 8 \text{ MeV corresponding to a mass thickness of } 400 \text{ mg/cm}^2$). The $2^+$ level parameters found here are $E_\gamma = 13.20\pm0.05 \text{ MeV}, \Gamma = 233\pm50 \text{ keV}$ and $\Gamma_0/\Gamma = 0.71\pm0.14 \text{ eV}$.

The region between $E_\alpha = 9 \text{ and } 12$ MeV has been studied in more detail in order to help resolve some of the resonance structure in this region. A resonance is apparent in $\sigma(52^0)$ near $E_\alpha = 11.7\pm0.15 \text{ MeV}$ which may or may not be present in $\sigma_{E2}(52^0)$ as well. However measurements of $\sigma_{E1}(52^0)$ clearly show a smooth behavior near this energy indicating this resonance must have $J^\pi = 2^+$. Between $E_\alpha = 9 \text{ and } 11.7$ MeV there is evidence for a broad E1 resonance at

![Graph](image-url)
Fig. 12.2-2. The energy dependence of \( \sigma_{E1}(52^\circ) \), \( \sigma_{E2}(52^\circ) \) and \( \cos \delta \) in the region of \( E_\alpha \) from 7 to 9 MeV.

**Fig. 12.2-3.** The cross section \( \sigma_{E2}(52^\circ) \) shown in Fig. 12.2-2, displayed here in more detail.

11.1 \pm 0.2 \text{ MeV} \text{ with } \Gamma_{\alpha M} = 1.7 \text{ MeV}, \text{ while the E2 cross section varies smoothly with energy, suggesting overlapping } 2^+ \text{ resonances.}

The region \( E_\alpha \) between 13 and 14 MeV has been studied in more detail at \( \theta_\gamma = 90^\circ \) with a 200 \text{ mg/cm}^2 \text{ natural C target, in order to try to resolve the two } 1^- \text{ resonances at } E_x = 17.14 \text{ and } 17.30 \text{ MeV seen in the } \text{^15N(p,}\gamma_0)\text{^16O} \text{ reaction.}^2 \text{ The results are shown in Fig. 12.2-4 where the arrows indicate the positions of these } 1^- \text{ resonances. Apparently only the upper resonance is made strongly in } (\alpha,\gamma_0) \text{ although there is evidence for weak excitation of the lower resonance.}

A discussion of the E2 strength seen in this reaction has been accepted for publication.\textsuperscript{3} Briefly, the E2 strength seen in this reaction is compared to the isoscalar sum rule limit\textsuperscript{4} in the top half of Fig. 12.2-5. For \( E_x > 12 \text{ MeV} \) the solid vertical bars represent the contribution to the EL sum rules from the \((\alpha,\gamma)\) cross section in the energy range covered by the horizontal bars. The total contribution from a 15.25 MeV 2\textsuperscript{+} state\textsuperscript{2,5} with \( \Gamma_\gamma \approx 0.8 \text{ eV} \) is also included. The solid bars below \( E_x = 12 \text{ MeV} \) represent E2 strength taken from a recent
Fig. 12.2-4. The 90° cross section from $E_\alpha = 13$ to 14 MeV observed with a 200 µg/cm² natural C target. Arrows point to the energies of known $1^-$ resonances. In addition to the ±15% uncertainty in the vertical scale due to the absolute normalization, there is an additional +0.02 -0.02 µb/σ uncertainty due to background subtraction. In the upper left the energy thickness of the target is indicated.

Fig. 12.2-5. Top half: The solid bars represent the measured E2 strength and the dashed bars the estimated strength. Bottom half: The measured and estimated E2 strength summed over 5 MeV intervals.

compilation. The total E2 strength seen from $E_x = 12$ to 28 MeV in ($\alpha,\gamma$) represents about 17% of the E2 $T = 0$ sum rule, while the additional known strength represents 25% of the sum rule, for a total of about 42%.

The resonances seen in ($\alpha,\gamma$) above $E_x = 12$ MeV may have significant strength in other particle channels, especially above 18 MeV where many channels are open. Evidence from other reactions for E2 strength above $E_x = 12$ MeV and below the GDR is scant, aside from the 15.25 MeV state mentioned above, the 16.5 MeV state ($T = 0, 0.2$) and a 2+ state near 19.1 MeV which is apparently $T = 1$. The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction shows evidence for E2 radiation in this energy range, but it is difficult to quantitatively estimate its strength. In the absence of detailed information about the wave functions for the ($\alpha,\gamma$) resonances, we can only roughly estimate the strength in other channels. We assume the important channels are $\alpha_0, \alpha_1$, and proton and neutron decay to the ground ($F_\frac{1}{2}$) and...
$6 \text{ MeV (p}^{1/2}_{3/2})$ states of mass 15. If we take the reduced width for decay in each of these channels to be proportional to the single particle limit $\gamma_{s.p.}$, with the same proportionality constant for each channel, then the factor \[ I \sim \frac{P_i \gamma_{s.p.}^2 (i)}{P_{00} \gamma_{s.p.}^2 (a)}, \] where $P_i \sim \gamma_{s.p.}$ is the Coulomb penetrability for channel $1$ and orbital angular momentum $\ell$, corrects the measured $(\alpha, \gamma)$ strength for what is lost in other channels. We do not suggest that this factor should be quantitatively correct for each resonance, but that it represents a correction which should roughly account for the opening of other channels. This factor increases from near unity at $E_\gamma = 13$ MeV to about 12 at $E_\gamma = 26.5$ MeV and when applied to the measured $(\alpha, \gamma)$ strengths yields the enhancements indicated by the dashed lines in Fig. 12.2-5, for a total estimated E2 strength of $\sim 70\%$ of the $T = 0$ sum rule. In Fig. 12.2-5 we have not enhanced the resonance near $E_\gamma = 16.5$ MeV, for which the measured $(\alpha, \gamma)$ strength is close to the radiative width given above; on the other hand the enhanced $(\alpha, \gamma)$ resonance strength near $E_\gamma = 15.25$ MeV is in agreement with the known radiative width for a $2^+$ level at this energy.

We make the following observations of $T = 0$ E2 strength in $^{16}O$ based on the measured plus estimated distribution (summed over 5 MeV intervals) shown in Fig. 12.2-5. 1) Most of the strength ($\sim 70\%$) allowed by the sum rule lies below 29 MeV. 2) The E2 energy centroid is $\sim 15$ MeV (although the discovery of higher strength could shift this upward). 3) The strength appears to be spread with a width of the order of 15 MeV. This should be contrasted with recent "screened TDA and RPA" calculations in $^{16}O$ which predict most of the $T = 0$ E2 strength to be concentrated in a narrow energy region somewhere between $E_\gamma = 15$ and 30 MeV (depending on the approximation).

It is interesting to compare these results with $(\gamma, p)$ and $(p, \gamma)$ measurements which show evidence for a "giant" E2 resonance in $^{16}O$ in the region $E_\gamma = 22-30$ MeV. A comparison of the magnitude and sign of the odd Legendre coefficients in the $(\gamma, p_0)^{2,8}$ and $(\gamma, n_0)^{10}$ angular distributions suggests that this E2 radiation is mainly isovector. Thus, there is evidence for an energy splitting between the isoscalar and isovector E2 strength distributions.

Additional details of this work, particularly concerning the E1 resonances, are currently being completed. Of particular interest is the comparison of the E1 $(\alpha, \gamma)$ resonances with the structure seen in the giant-dipole photo-absorption cross section (see discussion in 1973 Annual Report, p.113). Preliminary results indicate significant success in reproducing the shape of the GDR photo-absorption cross section between $E_\gamma = 20$ and 25 MeV (as seen in $^{15}N(p, \gamma_0)^{16}O$) in terms of a single broad resonance centered at $E_\gamma = 23$ MeV with $\Gamma = 3.5$ MeV and interfering with 5 narrow resonances whose energies and widths are determined by the measured energies and widths of the 4 observed $(\alpha, \gamma)$ resonances in this region, along with the resonance observed at $E_\gamma = 22.7$ MeV in $^{14}N(d, \gamma_0)^{16}O$. The success of this approach supports the possibility of an interpretation of the $^{16}O$ GDR structure in terms of a single "doorway" resonance (the broad resonance) and the narrower "intermediate structure" resonances observed in $(\alpha, \gamma)$ and $(d, \gamma)$. The doorway resonance may consist predominantly of 1 particle–1 hole configurations, while the intermediate structure resonances would presumably be more complicated. The absence of the "doorway" resonance in $(\alpha, \gamma)$ and $(d, \gamma)$ is noteworthy, and may be related to its high isospin purity relative to the narrower resonances by virtue of its broad width (short lifetime).

12.3 A Study of the Mechanism of the Radiative Capture of Low Energy Nucleons by $^{12}\text{C}$

D.L. Johnson

The mechanism of the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ radiative capture reaction has been investigated at low energies. The excitation function of the differential cross section at 90° was successfully measured, as described last year, in an energy region (2.7 ≤ E ≤ 3 MeV) where previous experimenters had been hampered by background problems. This was accomplished through the use of a combination of pulsed-beam time-of-flight technique, an anti-coincidence shielded spectrometer with pile-up rejection circuitry, and a background subtraction technique.

The purpose of this investigation was to test if the observed excitation function could be described with a conceptually simple theoretical E1 capture model which includes only direct capture plus capture involving intermediate compound states which include configurations where the 2+ first excited state of $^{12}\text{C}$ is coupled to an extra nucleon. The capture model makes use of incident wave functions generated with the coupled-channels approach of Mikoshiba, Terasawa, and Tanifuji which has been shown to reproduce the data for both the elastic and inelastic scattering of low energy nucleons by $^{12}\text{C}$.

To illustrate the proposed capture mechanism we show in Fig. 12.3-1 a schematic diagram of the direct component plus the additional contributions brought in by the excitation of the 2+ first excited state for E1 capture via the important 3/2+ incident channel.

A comparison of the experimental results with the prediction of the capture model is shown in Fig. 12.3-2. Here the two components of the $^{13}\text{N}$ ground
Fig. 12.3-1. Schematic diagram of the \( ^{12}\text{C}(p,\gamma_0)^{13}\text{N} \) reaction involving coupled-channels capture via excitation of the \( 2^+ \) first excited state of \( ^{12}\text{C} \). Incident channel is \( J^\pi = 3/2^+ \).

The resonance interference effect seen at an energy corresponding to the \( 3/2^+ \) state at about 6.9 MeV in \( ^{13}\text{N} \) is caused by interference between direct capture and capture involving the \( (2^+ \otimes s_{1/2}) \) configuration which is resonant in the \( 3/2^+ \) channel. The broad minimum at \( E_\gamma \approx 7 \) MeV is the result of destructive interference between direct capture and capture involving the \( (2^+ \otimes d_{5/2})^{3/2} \) configuration. The rise in cross section at higher energies is caused by the constructive interference of the same two contributions. The resonance corresponding to the \( 1/2^- \) state at 8.92 MeV in \( ^{13}\text{N} \) is an M1 transition and is not included in the simple model.

The capture model has also been applied to the \( ^{13}\text{C}(\gamma,n_0)^{12}\text{C} \) reaction which is related to its inverse, the neutron capture reaction, by detailed balance. Here too, the predictions of the model compare fairly well with measurements which include some angular distribution information.

Complete details of the experiment and the theoretical description are given in Ref. 4.

The detailed study of the $^{120}(a, \gamma_0)^{20}$Ne reaction discussed in Sec. 12.2 of this report raises two fundamental issues which should be examined further:

a) What is the energy distribution of isoscalar E2 strength in light nuclei?

b) What is the relationship between the El $(a, \gamma)$ resonances and the detailed structure of the Giant Dipole Resonance (GDR)?

The GDR in $^{20}$Ne as observed in the $^{19}F(p, \gamma_0)^{20}$Ne reaction is known to exhibit very strong intermediate structure which is not understood, and as such, seems potentially a good case to further test the ideas about $(a, \gamma)$ and intermediate structure presented in Sec. 12.2. In addition it is known that isospin-forbidden El a-capture into $^{24}$Mg, $^{28}$Si and heavier nuclei has a cross section the order of $\mu$b/GeV on the low energy side of the GDR, while for capture into $^{16}$O the cross section is much lower; thus it should be interesting to explore the transition region.

In Fig. 12.4-1 we show some preliminary data on the El cross section obtained for the $^{160}(a, \gamma_0)^{20}$Ne reaction at $\theta_\gamma = 90^\circ$ using a $330 \mu$g/cm$^2$ anodized tantalum foil ($\mathrm{Ta}_2\mathrm{O}_5$). It is apparent from Fig. 12.4-1 that, as in $^{120}(a, \gamma_0)^{160}$O, there is considerable structure in $(a, \gamma_0)$ in the GDR region which is apparently correlated with structure seen in $(p, \gamma_0)$. Whether the present results permit an interpretation of the sort discussed in Sec. 12.2 for $^{120}(a, \gamma_0)^{160}$O must await further analysis. Further measurements are underway, designed to answer the above questions.
12.5 The $^{89}$Y($p$,γ)$^{90}$Zr Reaction above the Giant-Dipole Resonance

D.R. Brown, K. Ebisawa, and K.A. Snover

The concentration of collective E2 strength in a "giant" resonance similar to the Giant Dipole Resonance (GDR) is a phenomenon which, if it exists for certain nuclei, might be expected to be a general feature over most of the periodic table like the GDR. The success of the experiment described in Sec. 12.6 in providing evidence for such a resonance in $^{208}$Pb has prompted us to look for similar effects in other mass regions.

Here we report the results of a study of the $^{89}$Y($p$,γ)$^{90}$Zr reaction from $E_p = 14$ to 22 MeV ($E_x = 22$ to 31 MeV), with emphasis on the energy dependence of the angular distribution. This energy region spans the location of the collective E2(EO) excitation seen in inelastic electron scattering at $E_x = 27$ MeV which, if E2, exhausts $>23\%$ of the isovector sum rule.¹

In this experiment the γ-rays from a self supporting $^{89}$Y target of 4.2 mg/cm² thickness were detected in a 10”×10” NaI detector with a plastic anticoincidence shield. Typical energy spectra of γ-rays, shown in Fig. 12.5-1, have about 3.6% resolution (FWHM) obtained with a total counting rate in the NaI of about $7\times10^4$ pulses/sec above $E_γ = 250$ keV. Spectra were taken at angles of 55°, 90°, and 125° to the beam axis in steps of 1 MeV. In the high energy portion of the spectra one can see two separated peaks. The highest one corresponds to the ground state transition ($γ_0$) and the next one consists of unresolved transitions to the first through fifth excited states ($E_x = 1.75$ to 3 MeV) of $^{90}$Zr ($γ_1 - γ_5$). The second peak is observed throughout the measured energy region and its area is obtained by summing counts from the peak region just below $γ_0$.

Fig. 12.5-1. The high energy part of γ-ray spectra from the $^{89}$Y($p$,γ)$^{90}$Zr reaction at $E_p = 20.0$ MeV and $θ = 55°$ and 125°. Arrows indicate the relative position of excited states in $^{90}$Zr.
As discussed in Sec. 12.6 the total cross section

\[ \sigma = 4\pi A_0 = 2\pi [Y(55^\circ) + Y(125^\circ)]. \]

We define the asymmetry factors

\[ a = \frac{Y(55^\circ) - Y(125^\circ)}{2P_1(55^\circ)} = A_1 - 0.68 A_2 \]

and

\[ a = \frac{A_1}{A_0} = a_1 - 0.68 a_3 \]

where

\[ Y(\theta) = \sum_{i=0}^{3} a_i P_i(\cos \theta) = A_0 [1 + \sum_{i=1}^{3} a_i P_i(\cos \theta)] \]

neglecting the \( a_4 \) coefficient. Then we also have

\[ a_2 = 2[1 - \frac{2Y(90^\circ)}{Y(55^\circ) + Y(125^\circ)}]. \]

The energy dependence of these quantities is shown in Fig. 12.5-2 for \( \gamma_0 \) and in Fig. 12.5-3 for \( \gamma_1 - \gamma_5 \), where data below \( E_p = 14 \) MeV was taken from Ref. 2.
In the excitation function of $A_0$ shown in Fig. 12.5-2 for the $^{89}\text{Y}(p,\gamma)^{90}\text{Zr}$ reaction, the $T_\gamma = 5$ Giant Dipole Resonance is seen at $E_p \approx 8$ MeV, and $T_\gamma = 6$ GDR components at $E_p \approx 11$ MeV and 12.5 MeV. Above $E_p = 14$ MeV the total cross section $4\pi A_0$ decreases smoothly by a factor of 5 up to $E_p = 23$ MeV. The asymmetry factor $A$, which arises from the interference between El and E2 or El and M1 radiations is constant above $E_p = 14$ MeV. The fractional asymmetry $a$ rises smoothly over this energy range, with no evidence for the inelastic electron scattering resonance seen at $E_X = 27$ MeV, which would correspond to $E_p = 18.8$ MeV. The $a_2$ coefficient also shows a striking trend toward positive values at higher energies.

As in the $^{208}\text{Pb}(p,\gamma)^{209}\text{Bi}$ example discussed above, these data do not provide enough information to extract the various complex reaction amplitudes and determine the E2 cross section as a function of energy. However, the situation is simpler here, where only p- and f-waves may contribute for E2 capture, and only s- and d-waves for El capture, with the unique channel spin $s = 1$. In order to get a better idea of the E2 cross section, we make some crude but simplifying assumptions. Just as El capture is predominantly d-wave, one would also expect E2 capture to be mostly f-wave. If we ignore s- and p-wave capture, along with magnetic dipole radiation, then

$$A_0 = 1.2 f^2 + d^2$$

and

$$A = 3.3 f d \cos(\phi_d - \phi_f)$$

$$A_2 = 1.4 f^2 - 0.50 d^2$$

using an obvious notation. The above equations include the effect of an $A_0$ coefficient, which may not be negligible in this approximation. Solving for $f, d$ and $\cos(\phi_d - \phi_f)$ from the measured values of $A_0, A$ and $A_2$, we find that $d$ decreases by a factor of 3 from $E_p = 14.0$ to 23.0 MeV, while $f$ is constant at a value corresponding to $\sigma(E2) = 4\pi f^2 = 1 \text{ mb}$. The phase factor $\cos(\phi_d - \phi_f)$ increases from $\approx 0.4$ to $\approx 1.0$ (with 50% errors) over this range. Thus, in this simplified model, the increase in the fractional asymmetry $a$ at higher energies is not due to an increase in $\sigma(E2)$ but is instead due to a decrease in $\sigma(E1)$ and an increase in $\cos(\phi_d - \phi_f)$. At $E_p = 23$ MeV roughly one-quarter of the total cross section is E2 in this analysis. A consequence of this is that the $a_2$ coefficient should be sizable (the above analysis yields $a_2 \approx 0.15$) and more detailed angular distribution measurements are planned to try to detect non-zero $a_3$ and $a_4$ coefficients. The above analysis is sensitive to our neglecting s- and p-wave capture and thus is useful only as a rough estimate of the E2 cross section. Further more detailed analysis is in progress.

These results stand in sharp contrast to the $^{208}\text{Pb}(p,\gamma)^{209}\text{Bi}$ results discussed in Sec. 12.6 which show evidence for an E2 resonance in the cross section asymmetry. In order to get a rough idea of our sensitivity for detecting a collective E2 resonance, we make an estimate of the $(p,\gamma)$ resonance cross section for an E2 resonance with width $I = 4$ MeV at $E_X = 27$ MeV, which exhausts 23% of the sum rule. Making the rough estimate that the proton decay probability is the same as for the GDR we estimate $\sigma(2, p,\gamma) \sim 1$ mb on resonance. This is comparable to the E2 cross section estimated above from the data and indicates that if such a resonance is present, we should be sensitive enough to see it.

12.6 Evidence for a Collective E2 Resonance in the Reaction $^{208}_{\text{Pb}}\text{(p,}\gamma)^{209}_{\text{Bi}}$

D.R. Brown, K. Ebisawa, F. Paul, † and K.A. Snover

For many years it has been known that a general feature of a wide variety of radiative proton capture measurements in the region of and just above the Giant Dipole Resonance (GDR) is the presence of an asymmetry in the angular distribution of $\gamma$-rays, about $\theta_{\gamma} = 90^\circ$, indicating the presence of E2 or M1 radiation interfering with the E1 radiation from the GDR. Here we report a study of this angular distribution asymmetry at energies well above the GDR in $^{209}_{\text{Bi}}$, in which the data yield evidence for a (collective) E2 resonance at an energy which corresponds to theoretical expectations for the Giant Isovector Quadrupole Resonance.

The present measurements were made using the proton beam from the 3-stage FN accelerator at the University of Washington. A self-supporting 2.8 mg/cm$^2$ $^{208}_{\text{Pb}}$ target was used, and the $\gamma$-rays were detected with a resolution of $\approx 3\%$ (see Fig. 12.6-1) in a $10'' \times 10''$ NaI detector$^2$ with a plastic anticoincidence shield. The statistical accuracy of the data was not sufficient to separately determine the areas of $\gamma_0$, $\gamma_1$, and $\gamma_2$, so the total yield of these three $\gamma$-rays was obtained by summing counts above the minimum between $\gamma_2$ and lower energy $\gamma$-rays. Gamma-ray spectra were measured at 55°, 90°, and 125° with respect to the beam axis, from $E_p = 17.5$ MeV to 25.0 MeV.

Now the most general expression for distribution of $\gamma$-rays including both dipole and quadrupole radiation is

$$ Y(\theta) = \sum_{i=0}^{\mu} A_i P_i(\cos \theta) = A_0 [1 + \sum_{i=1}^{\mu} a_i P_i(\cos \theta)] $$

Fig. 12.6-1. Typical spectra from the $^{208}_{\text{Pb}}\text{(p,}\gamma)^{209}_{\text{Bi}}$ reaction.

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where \( A_i \) and the \( P_i \) are Legendre Polynomials. Since the \( E2 \) and \( M1 \) contributions to the cross sections are expected to be small compared to the dominant \( E1 \) contribution, they should (except for accidental cancellations) show up most strongly in the odd Legendre coefficients, which arise from interference between radiations of opposite parity. Contributions from higher multipole orders should be negligible. Neglecting the \( a_4 \) coefficient, which can arise only from terms involving the \( E2 \) intensity, the total cross section can be written as

\[
\sigma = 4\pi a_0 = 2\pi [Y(55^\circ) + Y(125^\circ)].
\]

We also define the asymmetry factors

\[
A = \frac{[Y(55^\circ) - Y(125^\circ)]}{2P_1(\cos 55^\circ)}
\]

\[
a = A_1 - 0.68A_3
\]

and

\[
a = \frac{A}{A_0} = a_1 - 0.68a_3,
\]

where \( A \) and \( a \) are a measure of \( M1 \) or \( E2 \) radiation interfering with the dominant \( E1 \) radiation. These quantities are shown in Fig. 12.6-2 for \( E_p = 9.5 \) to \( 25.0 \) MeV, including previous measurements for \( E_p = 9.5 \) to \( 18.0 \) MeV. Below \( 18 \) MeV, \( A_0 \) is dominated by the GDR and by \( E1 \) decay of the Isobaric Analog Resonances (IAR),\(^3\) while above \( 18 \) MeV \( A_0 \) decreases smoothly. The asymmetry factor \( a \) rises steadily up to \( 18 \) MeV, with a few wiggles near the IAR's, while at higher energies a distinct resonance is apparent at \( E_p = 20 \) MeV, superposed on a smoothly rising background. The smoothly rising component in the asymmetry is a general feature of proton capture in a wide variety of nuclei for energies near the GDR, and its general features suggest it may be due to direct \( E2 \) capture interfering with the dominant \( E1 \) capture.\(^4\) The factor \( a \) shows a similar resonance behavior near \( 20 \) MeV. Now resonances in \( A \) or \( a \) can occur due to resonances in the dominant \( E1 \) radiation or in the weaker \( E2 \) or \( M1 \) radiation, or both. For example, the \( E1 \) IAR's, which show up strongly in \( A_0 \), also show resonance effects in \( A \) and \( a \). However, above \( 18 \) MeV the smoothly decreasing \( A_0 \) implies smoothly decreasing \( E1 \) capture amplitudes and suggests that the \( E1 \) phases vary slowly as well,\(^5\) in which case the anomaly near \( E_p = 20 \) MeV in \( A \) and \( a \) must be due to an \( E2 \) or \( M1 \) resonance.

The extraction of the resonance parameters from the interference measurements is a complex problem because of the many different reaction amplitudes which enter, corresponding to the different momenta involved in the capture process to each of the 3 final states. Here we consider only 1 final state,
and express the E1 amplitudes as

\[
\frac{i \phi_D(\ell j)}{D(\ell j)e^{i \phi_D(\ell j)}}
\]

and the E2(M1) amplitudes as

\[
\frac{i \phi_P(\ell j)}{E(\ell j)e^{i \phi_P(\ell j)}} = \frac{i \phi_P(\ell j)}{\Gamma(\ell j)e^{i \phi_P(\ell j)}} + \frac{F(\ell j)e^{i \phi_P(\ell j)}}{E - E_R + i \Gamma/2}
\]

where we assume that the amplitudes E(\ell j) and phases \phi_P(\ell j) (as well as D(\ell j) and \phi_P(\ell j)) vary slowly with energy above E_p = 18 MeV, and that the resonance near E_p = 20 MeV may be expressed in terms of Breit-Wigner amplitudes as shown (\ell and j refer to the orbital and total angular momentum, respectively, in the incoming channel). Then

\[
A = \sum_{\ell j' j''} C(\ell j l' j'') D(\ell j) E(l' j'') \cos \Delta \phi_{DE}
\]

\[
+ \sum_{\ell j' j''} C(\ell j l' j'') D(\ell j) F(l' j'') (\Gamma/2) \frac{[(\Gamma/2) \cos \Delta \phi_{DF} + (E - E_R) \sin \Delta \phi_{DF}]}{(E - E_R)^2 + \Gamma^2/4}
\]

where \Delta \phi_{DE} = \phi_D(\ell j) - \phi_P(\ell j'') and the C(\ell j l' j'') represent products of angular momentum coupling coefficients and odd Legendre Polynomials evaluated at the appropriate angles. The first term above represents the slowly varying component of A assumed to have the shape shown by the dashed lines in Fig. 12.6-2. The apparent symmetry of the portion of A in excess of the dashed line indicates that in the second term above, the factors involving (E - E_R) in the numerator sum approximately to zero and we are left with the resonance contribution to A:

\[
A_R = \frac{\Gamma^2/4}{(E - E_R)^2 + \Gamma^2/4} \sum_{\ell j' j''} C(\ell j l' j'') D(\ell j) F(l' j'') \cos \Delta \phi_{DF},
\]

which looks like a symmetric Breit-Wigner resonance whose strength is determined by a sum of interference factors (neglecting the energy dependence of the latter) from inspection, then, E_R = 20.0 MeV and \Gamma \approx 3.5 MeV.

The possibility that this resonance is an IAR corresponding to a single-particle orbital in the next major oscillator shell (above the N = 184 "gap") can be ruled out on the basis of the resonance strength: for any of the favorable orbitals (such as 2h11/2) the resonance strength can be found from the data, the expected \gamma-decay strength \Gamma can be calculated, and the result requires the ground-state proton width \Gamma_p to be unreasonably large, \approx 10 times bigger than the values found for the known IAR's, which would require the reduced proton width to be bigger by roughly the same factor, and would also be inconsistent with the absence of a resonance effect in elastic proton scattering. The only other possible explanation of this resonance (that we know) is that it is collective in the outgoing \gamma-channel. A collective M1 resonance at these energies
would be very surprising, as most of the M1 strength is expected to be at much lower energies \(\sim 5-9 \text{ MeV}\); also, no known mechanism would concentrate M1 strength at such a high energy. On the other hand, the excitation energy \(E_x = 0.995 E_p + 3.8 \text{ MeV} \approx 23.7 \text{ MeV}\) is in agreement with the energy of the collective E2 or E0 resonance observed at \(E_x \sim 22 \text{ MeV}\) in the \(^{208}\text{Pb}(e,e')^{208}\text{Pb}\) reaction,\(^{10}\) especially if one accounts in the present case for an upward shift in the resonance energy due to it being composite in the sum of \(\gamma_0 + \gamma_1 + \gamma_2\) yields (in the weak-coupling model, this upward shift would be \(\sim 0.9 \text{ MeV}\)). The total width observed here of \(\sim 3.5 \text{ MeV}\) also appears consistent with the data of Ref. 10, and we propose that the resonances seen in these 2 reactions correspond to the same (collective) excitation. This leads to the unique assignment of E2 since observation of the resonance in \((p,\gamma)\) rules out the E0 possibility.

An accurate estimate of the \((p,\gamma)\) resonance strength is hard to obtain in the case where many different resonance amplitudes may contribute to \(A_R\); however, a lower limit may be estimated by assuming equal coherent contribution from all the interference terms -- the result is 1 \(\mu\)b for the total E2 resonance cross section.\(^{11}\) Such a cross section constitutes a negligible fraction (< 0.1%) of the E2 isovector sum rule\(^{12}\) (the non-resonant background in the asymmetry, if E2, would also contribute negligibly to this sum). However, the total \(\gamma\)-absorption cross section integrated over all particle emission channels may well constitute a significant fraction of the sum rule. A consistency check may be made in the present case: if we assume the resonance strength is 60% of the E2 isovector sum rule,\(^{10}\) and estimate the branching ratio for ground-state proton decay as being roughly the same as for the GDR,\(^{13}\) then the predicted E2 resonance cross section for the \((p,\gamma_0 + \gamma_1 + \gamma_2)\) reaction is \(\sim 6 \mu\)b, which is consistent with the lower limit estimate from the data.

In conclusion, present evidence supports interpretation of the observed resonance as a collective E2 excitation, in agreement with theoretical expectations\(^{14}\) for the excitation energy of the E2 isovector giant-resonance. The total width of the observed resonance (\(\Gamma \approx 3.5 \text{ MeV}\), which is comparable to that of the GDR\(^{13}\) (\(\Gamma \approx 4 \text{ MeV}\)) even though the latter lies at a much lower excitation energy, is compatible with the (rather wide) range of possibilities presented in a recent calculation.\(^{15}\)

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<tr>
<td>20.0</td>
<td>0.74</td>
<td>0.94 ± 0.03</td>
<td>-0.12 ± 0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>0.66</td>
<td>0.92 ± 0.03</td>
<td>-0.14 ± 0.05</td>
<td>-0.07 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>0.79</td>
<td>0.92 ± 0.03</td>
<td>-0.14 ± 0.07</td>
<td>-0.08 ± 0.07</td>
<td>-0.003 ± 0.09</td>
</tr>
</tbody>
</table>
Further efforts are underway toward a more refined description of the E1-E2 interference process and a better understanding of the nonresonant background. Angular distributions have been measured at $E_p = 18.0$ and $20.0$ MeV in sufficient detail to permit separate determinations of the individual Legendre coefficients, and are shown in Fig. 12.6-3. For the $E_p = 18$ MeV data the solid curve corresponds to a Legendre fit with $l_{\text{max}} = 2$ (the fit with $l_{\text{max}} = 3$ is essentially identical) and the dashed curve with $l_{\text{max}} = 4$. For $E_p = 20.0$ MeV the solid curve is for $l_{\text{max}} = 2$ (the fit with $l_{\text{max}} = 4$ is essentially identical) and the dashed curve, for $l_{\text{max}} = 3$. The results are summarized in Table 12.6-1 and indicate the following general features: (1) $l_{\text{max}} = 2$ is sufficient to fit the data, and hence the cross section asymmetry is due to a non-zero $a_2$ coefficient, (2) the $a_2$ coefficient may be different at the two energies. Calculations are under way to try to understand these results, by including the effects of direct and "semi-direct" or resonant capture.

† Summer visitor, June, 1973, from SUNY, Stony Brook, N.Y.

5. A reasonable description of $A_2$ for $13 < E_p < 25$ MeV is in terms of the high-energy tail of the GDR, in which case a variation of the E1 phases of $\approx 10\%$ expected.
12.7 Radiative Capture of Fast Neutrons

E. Arthur, † D. Drake, † and I. Halpern

We report here the results of angular distribution measurements for the radiative capture of 14 MeV neutrons by several light nuclei. These measurements were carried out at the Van de Graaff neutron facility of the Los Alamos Scientific Laboratory. They bear on the quadrupole polarizability of nuclei as we shall explain below.

If we write the form of the radiation angular distribution in the customary way, \( W(\theta) = A_0[1 + \sum \limits_{i=1} a_i P_i(\cos \theta)] \) but keep only the first 2 terms in the sum, then

\[
a_1 \approx 1.75 \frac{W(55^\circ) - W(125^\circ)}{W(55^\circ) + W(125^\circ)}.
\]

[We have used here the fact that \( P_2(55^\circ) = P_2(125^\circ) = 0. \)] It is seen that the coefficient \( a_1 \), as it has been defined, provides a measure of the forward enhancement of emitted radiation. Now, it has been known for a long time that in radiative proton capture the coefficient \( a_1 \) generally rises gradually (aside from small fluctuations) from values near zero at energies in the neighborhood of the giant dipole resonance to values close to unity about 10 MeV above that resonance. This forwardness of the proton radiations is a sign of interference between amplitudes proceeding through intermediate states of differing parity, in this case states involving E1 and E2 captures. The interference provides an opportunity to learn something about the E2 strength function in nuclei from a comparison of the size of \( a_1 \) with the magnitude of the total capture cross-section which happens to be dominated by the E1 amplitude in this energy range. That is, one can hope to learn something about locations and widths of any E2 resonances of the target nuclei.

Unfortunately not all of the quadrupole capture amplitude arises from the excitation of a quadrupole oscillation in the target induced by the incident
proton. A considerable portion of the quadrupole amplitude can arise from direct capture of the proton. This direct background makes it difficult to obtain crisp, unambiguous information about strengths and locations of collective E2 excitations.

This difficulty does not apply to neutron capture. For neutrons the direct quadrupole capture amplitude is only \( \frac{1}{A} \) times the typical proton amplitude where \( A \) is the target mass number. Thus, if the angular distribution in fast neutron capture were to show an appreciable value for \( a_1 \), then we could safely attribute the interference to a quadrupole oscillation induced in the nucleus by the incident neutron.

Of course, neutron capture angular distributions are not as easy to measure as those of protons. It is difficult to have enough intensity for a measurement and at the same time to avoid systematic errors due to backgrounds from the target where the neutrons are being produced. Figure 12.7-1 shows the geometry of an arrangement where this background was reduced to tolerable levels which were moreover approximately independent of the angle between the neutron beam and the direction of observed radiation. With this arrangement and the necessarily large size of the capture target, it turns out that the neutron energy spread over the target is about 1 MeV under typical bombarding conditions (providing in this way, a welcome ironing out of possible fluctuations in \( a_1 \)).

In Table 12.7-1 we list the measured values of \( a_1 \) and \( a_2 \) for transitions to specified final states for four targets we have studied. The excitation energies for three of the targets (\(^{10}\)B, \(^{29}\)Si and \(^{40}\)Ca) lie several MeV above the giant dipole resonance. It is seen that for these targets the \( a_1 \) coefficients are small compared with those measured by protons of comparable energy on comparable mass targets (last column). This is in accord with our expectation that much of the proton \( a_1 \) value is due to direct captures. We note that the coefficient in \(^{12}\)C(\(n,\gamma\)) [here the capture comes below the giant dipole resonance] is large and negative.\(^2\) The neutron in this case is presumably inducing some sort of strong quadrupole oscillation as it comes into the target. We are in the process of trying to understand the magnitude and location of this apparent resonance.

Fig. 12.7-1. The geometry for fast neutron capture measurements. The deuterium beam \( D \) strikes a small tritium target \( T \). One uses the 14 MeV neutrons emitted in the plane \( P \) perpendicular to the beam. The target can be rotated in this plane between positions \( A_1 \) and \( A_2 \) to provide different observation angles at the NaI spectrometer \( S \) which is also in plane \( P \) at some distance behind the long collimator \( C \). (The distance between targets \( A_1 \) and the tritium is adjusted as one changes angles to keep the targets fully visible in the collimator.) The shadow bar \( SB \) shields the spectrometer from the tritium. The spectrometer to target distance is kept constant at all angles.
Table 12.7-1. Angular Distribution Coefficients for \((n,\gamma)\) with 14 MeV Neutrons
\(W(\theta) = \text{const}[1 + a_1 P_1(\cos \theta) + a_2 P_2(\cos \theta)]\)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>(E_x) (MeV)</th>
<th>(a_1)</th>
<th>(a_2)</th>
<th>(a_1) in comparable p capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{10}\text{B}(n,\gamma_0)^{11}\text{B})</td>
<td>25</td>
<td>0.09 ± 0.14</td>
<td>-0.43 ± 0.28</td>
<td>(^{10}\text{B}(p,\gamma_0) \sim 0.45)</td>
</tr>
<tr>
<td>(^{12}\text{C}(n,\gamma_0)^{13}\text{C})</td>
<td>18</td>
<td>-0.43 ± 0.27</td>
<td>0.07 ± 0.4</td>
<td>(^{11}\text{B}(p,\gamma_0) \sim 0.25)</td>
</tr>
<tr>
<td>(^{29}\text{Si}(n,\gamma_1,2)^{30}\text{Si})</td>
<td>25</td>
<td>0.07 ± 0.18</td>
<td>0.36 ± 0.2</td>
<td>(^{39}\text{K}(p,\gamma_0))</td>
</tr>
<tr>
<td>(^{40}\text{Ca}(n,\gamma_0)^{41}\text{Ca})</td>
<td>22</td>
<td>-0.1 ± 0.1</td>
<td>0.03 ± 0.2</td>
<td>(^{41}\text{K}(p,\gamma_0) \sim 0.3)</td>
</tr>
</tbody>
</table>

It appears that it will be difficult to significantly reduce the statistical errors of these measurements in the near future. The best compromise between the considerations of running time and the investigation of the most significant issues suggest a survey of additional nuclei especially if we include in the angular distribution studies the higher-lying unresolvable final states of these nuclei.

† Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
2. Large negative values for \(a_1\) just below the giant resonance have also been reported for the \(^{12}\text{C}(\gamma,\gamma_0)^{11}\text{C}\) reaction by J.W. Jung, J.S. Hewitt and K.G. McNeill in Proc. Int. Conf. Photonuclear Reactions and Applications, Asilomar, CA (B.L. Berman, ed.) p. 158.
13. FISSION

13.1 Measurement of Conversion Electrons Preceding Delayed Fission in $^{235}$U

I. Halpern, R. Heffner, J. Pedersen, G. Sletten, H. Swanson, and R. Vandenbosch

We have continued our work to measure the energy spectrum of conversion electrons preceding delayed fission in $^{235}$U which was reported last year. Several major improvements have been made in the experimental apparatus and spectra have been collected which are consistent with a rotational band spectrum corresponding to a deformation more than twice that of the stable ground state. The evidence is not yet conclusive, however, and the measurements are being continued.

a. Modifications to the detector system

The detection scheme is shown in Fig. 13.1-1. Conversion electrons are bent into solid state Si(Li) detectors under the action of a uniform magnetic field and are detected in delayed coincidence with the fission fragments. The fission fragments themselves are detected with a recoil-type detector.

We replaced the two laboratory made Si(Li) electron detectors in our original system with a single 300 mm$^2$, 3 mm thick circular detector purchased from Kevex Corporation. A Tennelec model 161A preamplifier was modified to be able to cool the field effect transistor and feedback resistor. (The detector and components were cooled to $-100^\circ$C.) This system performed satisfactorily yielding $\pm 1.2$ keV full-width-half-maximum (FWHM) electron resolution at 62 keV electron energy at low counting rates and less than 2 keV FWHM at 20K Hz.

The fission fragment detector was modified so that each of the three counters was a distinct and separate unit, each with its own detector and Ni cover foil instead of being part of the composite detector originally used. The method of detector fabrication was also changed; the new wafers were surface barrier detectors fashioned after Hansen et al. This system was 100% reliable; that is, we had no detector failures in any of the three original units over a 10 month period.

The details of the improved detection system can be found in Ref. 4.
b. Experimental Results

Twenty MeV deuterons were used to bombard a thin (=5 μg/cm²) 236U target. The experimental decay curve for electrons in coincidence with delayed fission fragments is shown in Fig. 13.1-2. The half-life of the 236U ground state isomer obtained from previous measurements of the delayed fission fragments alone is $125 \pm 15$ nsec, in good agreement with our result.

A normalized chi-squared correlation was calculated to search objectively for the presence of structure in the electron energy spectrum corresponding to E2 transitions from a rotational band in the even-even isomer. Our experimental energy resolution was sufficient to resolve the $L_{11}, L_{111}, M$ and $N$

![Decay curve](image)

**Fig. 13.1-2.** Decay curve for electrons in coincidence with delayed fission fragments from 236U. The data for the first 102 nanoseconds were corrected for a 12% loss in yield due to the loss of isomer events decaying in flight behind the fragment detectors.

![Fingerprint spectra](image)

**Fig. 13.1-3.** Data used in computation of normalized chi-square correlation (Runs A1 + A2). Shown above are the computer generated ideal spectra used in the correlation for the transitions indicated. These standard spectra are weighted by the electron detection efficiencies.
components of each conversion line. The data were binned into 1 keV intervals
and the correlation function between the efficiency weighted L and M "finger-
prints" and the data was calculated at each 1 keV interval. A correlation
value of one indicated the presence of an E2 transition. The data and "finger-
print" spectra are shown in Fig. 13.1-3 and the correlation function in Figure
13.1-4. The adiabatic rotor model predicts that the energy of a rotational
band state of spin J is given by $E(J) = AJ(J + 1) + \cdots$, from which we have $E = E(J + 2) - E(J) = A(4J - 2)$ (neglecting higher order terms) where $A$ is inversely proportional to the moment of inertia.
The two minima in Fig. 13.1-4 where the ordinates reach down near the value one
may indicate the presence of $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ rotational band transitions, as
shown in Fig. 13.1-5 where we have plotted the extracted gamma energies vs
$4J - 2$. The value of $A$ at the normally deformed ground state is 7.55 keV, about
twice that seen in Fig. 13.1-5. Part of the structure in the electron energy
spectrum associated with delayed fission is therefore consistent in energy and
relative spacing with a rotational band having a moment of inertia about twice
that of the ground state band$^5$. This is qualitatively what one expects for a
band in the highly deformed fission isomer state.

This interpretation of the ob-
servations is however not consistent
with the observed relative intensities
of the assumed $4^+ \rightarrow 2^+$, $6^+ \rightarrow 4^+$ and
$8^+ \rightarrow 6^+$ transitions. These were found
to differ from those predicted by a
simple model calculation for the
$^{236}\text{U}(d,\text{pn})^{236}\text{mU}$ reaction.$^4$ (The "$8^+ \rightarrow 6^+$
intensity" was extracted by summing the
counts in the relevant energy bins based
upon the A value in Fig. 13.1-5). Further-
more, a malfunction of the magnet control device during the data collection
yielded some uncertainties in the electron detection efficiencies. For these
reasons, and because only a relatively small number of events were collected,
the evidence for a rotational band, though tempting, is not yet compelling

Fig. 13.1-4. Normalized chi-squared corre-
lation. Data for a) were binned
slightly differently than the data for
b). See Ref. 4. A value for $\chi^2$/NORM
equal to one indicates the presence of
electron lines corresponding to an E2
gamma transition.
and the experiment is being continued at the Niels Bohr Institute in Copen-


![Graph](image)

Fig. 13.1-5. Plot of deduced E2 gamma transition energies vs 4J - 2. The slope of this line yields a moment of inertia more than twice that of the stable ground state.
14. ATOMIC PHYSICS

14.1 Progress Report on Inner-Shell Ionization by Heavy Ions in the MeV Energy Range

D. Burch

A survey\(^1\) has been prepared on theoretical and experimental work on inner-shell ionization by projectiles heavier than an alpha particle at energies greater than 1 MeV. Available data extend from 5 to 300 MeV; Bi ions are the heaviest projectiles employed so far. The following topics are covered briefly: historical review, ionization mechanisms, multiple ionization and spectral measurements, fluorescence yields, ionization probability measurements, x-ray production cross sections, united-atom phenomena, and the effects of nuclear Coulomb excitation. The literature survey was intended to be thorough through August 1973.


14.2 K-Shell Ionization of Carbon by 1 to 18 MeV Protons

D. Burch and L. Graham

K-shell ionization by protons has been successfully described by both the binary encounter approximation (BEA) and by the plane wave Born approximation (PWBA) at proton energies near or below the maximum in the cross section. Empirically, the BEA model has proved to be more accurate in this region but the origin of this has not been explained theoretically. At energies well above the maximum, the conditions for the (Bethe-Born) asymptotic form of the PWBA are well met and these calculations should yield the correct cross section: \(\sigma(E) \approx (\ln CE)/E\), where \(E\) is the collision energy in units of the target k-shell binding energy and \(C\) is a constant approximately equal to 4. The BEA model, on the other hand, predicts a simple \(1/E\) form which in principle is incorrect but numerically does not yield a significantly different slope at high energies.

To investigate the asymptotic region we have measured the x-ray production cross section in proton collisions with thin carbon foils at energies at and above the maximum which occurs at 1 MeV. Experimental factors which could affect the relative x-ray yields are the possibility of carbon build-up on the target and the vastly changing gamma-ray background with increasing proton energy. The carbon build-up problem was eliminated by completely surrounding the 20 \(\mu\)g/cm\(^2\) target with a liquid-nitrogen cold trap. Carbon K x rays (280 eV) were detected with a thin-window gas-flow proportional counter which was heavily shielded with Pb to reduce the background. The peak-to-background ratio and shape of soft x-ray region of the spectrum did not change significantly with proton energy. The measurements were made at a constant beam intensity to remove any possible systematic errors in current integration. Including the uncertainty in the fluorescence yield (\(\omega_X = 2.4 \pm 0.4 \times 10^{-3}\)) our absolute values for the ionization cross section determined from the x-ray cross sections agree within the respective uncertainties.
with the low-energy Auger-electron measurements of Toburen\textsuperscript{1} which are independent of the precise value of \( \omega \). The results are presented in Fig. 14.2-1 the relative experimental uncertainties are less than 4\%. It is seen that the BEA cross section falls off too rapidly at high energies and the PWBA result is more accurate.


14.3 Simple Model for K x-ray and Auger-Electron Energy Shifts in the Presence of Multiple L-Shell Vacancies

D. Burch, W.E. Meyerhof,\textsuperscript{†} and L. Wilets

High-energy heavy-ion collisions result in the production of high degrees of multiple ionization. In contrast to excitation by photons, electrons, or high-energy protons, K-shell ionization by heavy ions rarely results in a single K vacancy but rather the typical ionization states produced include a K vacancy plus multiple L and M shell vacancies. The observed K x rays and Auger electrons from these configurations are shifted in energy with respect to the single K vacancy transitions; x rays are shifted to higher energies and Auger electrons to lower energies. The effects of M vacancies are relatively small unless very high degrees of ionization are created. To a fairly good approximation, the K shell transition energy shifts per L vacancy are proportional to the number of L vacancies.

A simple electrostatic potential model has been described\textsuperscript{1} which gives an intuitive and yet quantitative estimate of the energy shifts per L vacancy. A comparison with Hartree-Fock-Slater calculations was used to test the model predictions. The model predictions are surprisingly accurate for the x-rays shifts (within 5\%) at intermediate and high Z but are less reliable for the Auger shifts in this region. Fortuitously, the model predictions are very accurate for the low-Z Auger electron energy shifts.

\textsuperscript{†} Permanent address: Department of Physics, Stanford University, Stanford, CA.

14.4 Inner-Shell Ionization of Pb at Zero Impact Parameter in Cl + Pb Collisions

D. Eurch, W.B. Ingalls, R. Vandenbosch, and H. Wieman

It has been proposed recently by Muller, Peitz, Rafele, and Greiner that atomic collisions between very heavy atoms might be used as a means of observing a fundamentally new process in electrodynamics. This process, which they point out is analogous to an "autoionization of positrons", requires that a heavy ion produce a K vacancy in a high-Z target atom on a very close trajectory. A detailed analysis of the feasibility of the experiment they propose requires a knowledge of the K-shell ionization probability in head-on collisions in ion-atom systems with $Z_1 + Z_2 \geq 172$. Although this particular measurement is not possible with tandem Van de Graaff facilities, experiments can be carried out which will be useful in assessing available ionization theories which must be used to predict and interpret the cross sections of interest.

More generally, since the ionization probability is a measure of the differential cross section it provides a sensitive test of the ionization model. For example, independent formulations of the direct Coulomb ionization process can, using the same collision approximations, yield identical total cross sections for K-shell ionization but predict ionization probabilities at zero impact parameter which differ by more than a factor of ten.

The absolute K-shell ionization probability at zero impact parameter has been measured in a coincidence experiment with incident Cl ions having energies from 50 to 100 MeV. Total K-shell ionization cross sections are also reported over a larger energy range. The data are compared with theoretical predictions based on the assumption of pure Coulomb ionization as formulated in the binary-encounter approximation (BEA), the semi-classical approximation (SCA), and the plane wave Born approximation (FWBA). It is shown that the good agreement of the total cross sections with nonrelativistic calculations using

Fig. 14.4-1. Cross section for K-shell ionization of Pb by Cl projectiles. Open circles are the measured values, the theoretical curves are: A - classical BEA which also coincides with an unmodified PWBA result; B - a SCA calculation; C - a modified BEA calculation; and D - a modified PWBA result including an additional reduction of the cross section intended to account for an increase of the target electron's binding energy due to the presence of the projectile. These curve are discussed in detail in Ref. 2.
Fig. 14.4-2. K-shell ionization probability of Pb by Cl ions at zero impact parameter. Open circles are the measured values, the theoretical curves are: I - classical BEA; II - a modified BEA result; and III and IV are approximate SCA predictions. These curves are discussed in detail in Ref. 2.

Fig. 14.4-3. L-shell ionization probability of Pb by Cl ions at zero impact parameter. The solid line is simply drawn through the data points. A theoretical analysis of the data has not been completed.

A straight-line, constant velocity projectile trajectory is to a large extent due to a fortuitous cancellation of the inadequacies of this over-simplified model. Recent impact parameter formulations of the BEA model, including corrections for projectile retardation and deflection and an approximate treatment of relativistic effects, qualitatively reproduce the observed energy dependence of the cross sections and ionization probabilities but overestimate the absolute values by a factor of about 3. Approximate, closed-form SCA results without these corrections also reproduce the energy dependence but underestimate the ionization probability by a factor of 2 to 3.

The data are presented in Figs. 14.4-1 and 14.4-2; full details of the
experiment and analysis are presented elsewhere. L-shell ionization probabilities for the same collisions are presented in Fig. 14.4-3.


14.5 Search for United-Atom X-ray Transitions in 60-MeV Cl + Pb

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

When an inner-shell vacancy is created in a heavy-ion collision there is some probability that the vacancy state will decay before the collision partners are well separated. The subsequent energy of an x-ray transition in such an event would depend upon the internuclear separation at the time of decay. Molecular orbital energy calculations show that even for separations as large as twice the K-shell radius of the heavier partner, a K x-ray transition to this shell would have a significantly increased energy. The experimental identification of such transitions presents a challenging new problem in the field of inner-shell ionization in heavy-ion collisions. Although it is still quite speculative in terms of available experimental data, the observation of "united-atom" or "molecular-orbital" (MO) x-rays might provide a means of studying the atomic properties of transiently-formed super-heavy atoms regardless of the stability of the super-heavy nuclei.

Based on the K-shell transition rates, the collision velocity and trajectory, and the Cl + Pb correlation diagram,1 the intensity of MO x-rays in 60-MeV Cl + Pb at impact parameters of 1 to 4 fm can be estimated to be 2 to 4% of the total number of K x rays produced on this range of trajectories. From the measured ionization probabilities and cross sections,2 the fraction of x rays produced on these trajectories is 7.5 × 10⁻⁴ of the total number of x rays produced on all trajectories. An experimental search for this intensity was carried out with the apparatus and method previously described,2 the amplifier gains were adjusted to include the united-atom x-ray region. The accumulated results representing 5 days of integrated-beam time are shown in Fig. 14.5-1.

The intensity observed above the normal K x-ray energies which could be attributed to united-atom K x-ray transitions in Cl + Pb was found to be a factor of 2 to 4 higher than estimated. The apparent cut-off energy is also slightly higher than the maximum united-atom transition energy, but this result could be accounted for in terms of the effect of the uncertainty principle on the energy levels during the collision ("collision broadening").

Several experimental tests and further analysis must be made before this intensity can be identified as united-atom K x-ray transitions. Contrary to our previous expectations, recent calculations of the impact parameter dependence of K-shell ionization in Cl + Pb together with the Cl + Pb correlation diagram indicates that roughly the same relative MO intensity should be observed in
the total x-ray spectrum which includes contributions from all impact parameters. Figure 14.5-1 shows that this intensity is, however, only seen in the coincidence spectrum which is limited to head-on collisions only.

This latter result lends support to a suggestion of Miller\(^1\) who has pointed out that united Pb + Pb L x-ray transitions have the same cut-off energy as united Cl + Pb K-shell transitions. If the intensity observed is in fact due to Pb + Pb collisions in the recoil interaction, then it would only be observable following a head-on collision (in the coincidence spectrum) since otherwise there is insufficient energy transfer for L-shell ionization in the recoil interaction. From measurements of the target thickness dependence of the L-shell ionization probability at zero impact parameters, the recoil Pb + Pb L x-ray production cross section is \(\leq 4000 \text{ b}\.\) This limit is on the order of the primary Cl + Pb L x-ray cross section and therefore is not low enough to rule out the recoil interpretation. Having, at present, only a limit and not an absolute value for this cross section, we are also unable to confirm this interpretation.

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1. B. Miller, private communication.
2. See Sec. 14.4 of this report.

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14.6 Electron Loss in 10-MeV He\(^+\) and Ar

D. Burch, D. Schneider, \(^\dagger\) N. Stolterfoht, \(^\dagger\) and H. Wieman

In earlier work\(^1\) at this Laboratory it was found that a broad peak dominating the electron energy spectra at 90° for 30- to 40-MeV O\(^{4+}\) and O\(^{5+}\) ions on Ar is due to outer electrons of the projectile ion being scattered by the target. A simple binary encounter approximation (BEA) based on elastic electron scattering fit the shape and energy of the electron loss peak. The details of the model based on this approximation are described elsewhere.\(^1\) The basic assumptions are that the electron has an incident velocity vector which is the sum of the projectile ion velocity and the electron orbital velocity. The electron is assumed to scatter in the screened Coulomb field \(V = (ze/r)\exp(-r/a)\) of the target. The projectile ion field is ignored except its role in determining the initial orbital velocity distribution. According to the model the shape of the loss peak (i.e., of the peak in the observed spectrum) is primarily determined by the electron
orbital velocity distribution with the details of the screening playing a less significant role. In the O\(^{4+}\) measurements it was found that the correct 2s velocity distribution (\(f_{2s}(v)\)) provided the best fit to the data which suggested the possibility of using electron loss spectra to probe the velocity distributions of selected electron shells.

We now report electron measurements for 10-MeV He\(^+\) on Ar which can be fitted only with a 1s velocity distribution (\(f_{1s}(v)\)), thus confirming the sensitivity of these measurements to velocity distributions. We have measured absolute double differential cross sections from 25° to 130° which provide a stricter test of the BEA electron loss model than was possible with our earlier relative cross sections at 90°. Cross sections were also measured for 30-MeV O\(^{4+}\) and O\(^{6+}\) at 25 deg and an angular distribution was determined for 55-MeV Cl\(^+\) on Ar.

The measurements were made using a parallel plate electrostatic electron analyzer and a gas jet target system that was made available by Hahn-Weitner Institut for temporary use at the tandem. The Laboratory's on-line computer was used to store the data and to control the analyzer.

In isolating the 10-MeV He\(^+\) electron loss spectra, background from the target electrons was removed by subtracting measured electron spectra for He\(^{++}\). This results in an over-subtraction since the target electron production increases with projectile charge state. The problem was minimized in the He\(^+\) electron measurement by choosing a projectile velocity sufficiently large to place the loss peak at \(\approx 1000\) eV in a region above the main strength of the target electron contribution. The target gas was sufficiently thin to both insure single rather than multiple interactions and to permit the use of beam charge integration to determine cross sections. The angular distribution measurements include angular corrections for variations in the effective target region seen by the electron analyzer. The density of the target jet was determined by calibrating with electron measurements in which the scattering chamber was filled with a uniform known pressure of target gas. A Baratron capacitance manometer was used to determine the absolute target pressure. The experimental uncertainty in the cross sections is estimated to be \(\pm 25\%\).

Figure 14.6a shows the electron loss spectrum for He\(^+\) on Ar at 110 deg after subtraction of target electrons. The BEA prediction is shown for comparison. There are no free parameters in this calculation. The scaling of the 1s velocity distribution used is determined by the He\(^+\) ionization potential. (The Thomas-Fermi screening length (\(a = 0.885 a_0 Z^{-1/3}\)) was used in all cases.) Included in the figure is the BEA prediction using a 2s distribution to demonstrate the sensitivity of these measurements to the velocity distribution. The ionization energy used was the same as for the 1s case.

The BEA model works well at back angles but as shown in Fig. 14.6-1b the model overestimates the forward cross section (by a factor of 4.5 at 35°). At forward angles the scattered electron remains in the vicinity of the projectile ion longer than in the backscattered case; it is possible therefore that ignoring the projectile ion field, as is done in BEA, is a less valid assumption at forward angles.

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Fig. 14.6-1. a. Electron loss energy spectrum at $110^\circ$ for 10 MeV He$^+$ on Ar compared with BEA using correct 1s velocity distribution (solid line) and with BEA using instead a 2s velocity distribution (dashed line). The points show the difference spectrum of He$^+$ on Ar and He$^{2+}$ on Ar. b. Angular distribution for electron loss from 10 MeV H$^+$ on Ar compared with BEA.

In Fig. 14.6-2 the BEA calculations have been scaled to match the magnitude of cross sections at $25^\circ$ for O$^{4+}$ minus O$^{5+}$ and He$^+$ minus He$^{2+}$ demonstrating that BEA although failing in magnitude still gives the correct shape and position at forward angles. The subtraction method does not work as well for oxygen as for He in isolating the loss fraction because oxygen-ion collisions produce relatively many more target electrons. There are also contributions from the inner-shell projectile electrons which are charge state dependent and therefore not as rigorously subtractable. The error due to over-subtraction could be as much as $25\%$. The small peak on the high-energy side of the oxygen electron loss spectrum is due to projectile Auger electrons.

Electron spectra from 55 MeV Cl$^{7+}$ ions on Ar were measured but it was not
possible to make a quantitative separation of the 3s projectile electrons from
the large contribution from other sources.

† Permanent address: Hahn-Weitner Institut, Berlin.
2. See Sec. 4.4 of this report.

14.7 Mechanisms for Electron Production in High-Energy $O^{++} + O_2$ Collisions

D. Burch, J.S. Risley, D. Schneider, † N. Stalderfoht, † and H. Wieman

Heavy-ion collisions result in the production of copious amounts of
electrons. This is well known in nuclear physics laboratories since these elec-
trons destroy thin particle detectors, degrade detector energy resolution, and
seriously aggravate the problem of accurate beam-current integration. On an
atomic physics basis, however, the role of the ejected electron distribution
is not at all so grim. The absolute cross sections for electron production differen-
tial in electron energy and ejection angle provide the ultimate test of ion-
ization theories and reflect dramatically the several mechanisms which lead to
electron emission both discrete and continuous.

Cross sections for electron production in oxygen-ion single collisions
with oxygen gas have been studied as a function of the projectile charge state
and energy. Measurements were made at several angles over an electron energy
range of 10 to 5000 eV. The data are presented in Figs. 14.7-1, -2, and -3; ex-
erimental uncertainties in the absolute values are ±25%. Prominent features
of the spectra are indicated, with T and F denoting whether the source of electrons
is the target or projectile. The label "soft collisions" indicates the electrons
which received the minimum momentum transfer. In events leading to these elec-
trons, the ionization occurs only as a result of the electron's binding to the
atom since the momentum transfer alone is insufficient to ionize. The opposite
is true of the electrons in the "hard collisions" peak. These electrons have
received the maximum momentum transfer consistent with energy-momentum con-
servation and correspond to an ionization process which, to first order, is indepen-
dent of the electron's binding energy. The centroid energy of this peak is given by
$E_a = (4m/M)E \cos^2 \theta$, where $E$ and $M$ are the projectile energy and mass; the peak
width reflects the velocity distribution of the target electrons. The energy
loss of a fast projectile is roughly equally divided between "soft" and "hard"
collisions -- an approximate theoretical result which can be used to estimate
the relative yield of low- to high-energy knock-out electrons. At 30 MeV, the
intensity of the "soft" collision peak increases with projectile charge state
from $4^+$ to $8^+$ by more than a factor of 5 while the "hard" collision intensity
increases by only ~25%. This result implies that the effect of electron screening
of the projectile nuclear charge is much more important for those collisions in-
volving small momenta transfer.

The electron-loss peak$^2,3$ constitutes electrons stripped from the L shell
of the incident oxygen ion. The total yield from $O^{++}$ ions (2 L-shell electrons)
is twice that of the $O^{5+}$ ions as expected.$^2,3$ The small intensity in the $O^{6+}$
Fig. 14.7-1. Cross sections for electron production as a function of the projectile charge state.

spectrum (Fig. 14.7-1) reflects a combination of the $^{5+}$ contamination of the beam and the fraction of $^{6+}$ ions in metastable states, for example $1s^12s^2$. The forward peaking of the electron-loss yields shown in Fig. 14.7-2 is consistent with a simple elastic scattering model of this process.
Auger electrons following K-shell vacancy production in the target and projectile are also observed. Auger electrons emitted from the moving projectile are kinematically shifted by an amount simply determined from a velocity triangle. After correction for kinematic effects on the solid angle, it is found that the Auger electron production in the target and projectile are equal in O\textsuperscript{4+} collisions ($\sigma_A = 6 \times 10^{-18}$ cm$^2 \pm 25\%$).

In going to O\textsuperscript{6+} ions, the target Auger production cross section increases by a factor of 30 -- further evidence of the importance of the projectile charge state to the interpretation of inner-shell ionization measurements.\textsuperscript{4}

A surprising result of these measurements was the presence of strong K-Auger emission from O\textsuperscript{5+} ions. Simple K-shell ionization of an O\textsuperscript{5+} ion in its ground state ($1s^22s1$) cannot give rise to an Auger transition since two outer-shell electrons are required. This intensity must arise from one or both of the following processes: K-shell excitation to a bound state ($1s^22s1 \rightarrow 1s^12s^1n\ell$) or K-shell ionization followed by, or in conjunction with, electron capture ($1s^22s1 \rightarrow 1s^12s^1 + 1s^12s^1n\ell$). In either case the presence of these electrons shows that K-vacancy production is not necessarily dominated by simple K-shell ionization even in those cases where an alternative process is not mandatory.

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1. Permanent address: Hahn-Meitner-Institut, Berlin.
2. The experimental apparatus is described briefly in Sec. 14.6 of this report.
4. See Sec. 14.6 of this report.

14.8 High-Resolution Auger Spectra Excited in 30-MeV Oxygen Collisions

D. Burch, J.S. Risley, D. Schneider,\textsuperscript{†} N. Stolterfoht,\textsuperscript{†} and H. Wieman

Rare gas Auger spectra produced in oxygen-ion collisions reported previously\textsuperscript{1} were measured with a resolution of $\sim 2\%$ FWHM. At that resolution, structure in the broad Auger groups was not observed and further it was suspected that due to the dense number of states produced, even higher resolution would not reveal individual lines. Higher resolution measurements ($< 0.1\%$), however, have shown that this is not the case and the Auger spectra have proven to be, although
Fig. 14.8-1. Neon K-LL Auger spectrum observed at 150° in 30-MeV O^{5+} + Ne.

more complicated, even richer in structure than the corresponding x-ray spectra.

Examples of K, L, and M Auger spectra are presented in Figs. 14.8-1, -2, and -3. The spectra were measured with a parallel-plate electrostatic analyzer which has been described in detail elsewhere. The electrons were decelerated to ∼10 eV prior to energy analysis to increase the resolving power.

In Fig. 14.8-1 the highest energy peak corresponds to n = 0 in initial vacancy states KLM with the next three lower-energy groups having n = 1, 2, and 3. From the approximately equal energy spacing observed and expected from atomic structure calculations, evidence for n = 6 transitions are also present which constitute the maximum degree of L-shell ionization possible if K-LL Auger decay is to occur. The ratio of the n = 0 intensity to the total yield provides

Fig. 14.8-2. Argon L-MM Auger spectrum observed at 150° in 30-MeV O^{5+} + Ne.
Fig. 14.8-3. Krypton M-NN Auger spectrum observed at 150° in 30-MeV O5+ + Kr and 5-MeV protons + Kr.

valuable information for the analysis of the mean fluorescence yield. The intensity above 805 eV is tentatively attributed to Auger decay following single K-shell excitation to high-lying bound states.

The Ar L-MM spectrum of Fig. 14.8-2 is similar. The highest energy group of four lines represents LMN defect configurations with n = 0; the next two groups correspond to n = 1 and 2. The isolated line at 100 eV is easily identified from systematics of optical spectra to be 2p53s2 + 2p6, thus corresponding to the maximum degree of multiple ionization consistent with an Auger decay.

The M-NN spectrum of Kr, Fig. 14.8-3, was quite surprising — where the largest difference between proton and heavy-ion excitation was expected, the minimum was observed. Except for the extra intensity near 60 eV, the two spectra are very similar. The origin of this similarity is uncertain. Possible explanations might be: (1) the total N-shell ionization cross section is smaller than that of the M shell, reducing the probability of MNN multiple ionization or (2) the dominating source of M-shell ionization is secondary processes such as photo absorption or ionization by collision-produced electrons. Each of these sources of ionization would lead to a spectrum equivalent to proton ionization.

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Several authors have recently reported that x-ray production cross sections, $\sigma^X$, in heavy-ion collisions at a fixed energy increase nearly exponentially with the projectile charge state. A rise in $\sigma^X$ could be due to a charge-state dependence of the inner-shell ionization cross section $\sigma = \sigma^X(x\text{ ray}) + \sigma^A(\text{Auger})$ or from a charge state dependence of the outer-shell ionization cross sections which affect the inner-shell x-ray yields through the fluorescence yield $\omega = \sigma^X/\sigma$. To determine the relative contributions of these effects we have measured $\sigma^X$ and $\sigma^A$ for the Ne K shell in 50-MeV Cl$^{14+}$ Ne at incident charge states of 5+ to 15+. Auger-electron and x-ray spectra are shown in Fig. 14.9-1 and the data for $\sigma$ and $\omega$ are presented in Fig. 14.9-2.

Partial results of this work can be summarized:

1. Both $\sigma$ and $\omega$ increase with increasing projectile charge state. From 5+ to 15+, $\omega$ increases by a factor of 7.2 and $\sigma$ increases by a factor of 2.8 showing that the 20-fold increase in $\sigma^X$ is primarily due to the rise in the mean fluorescence yield.

This result is the opposite of that recently deduced from the charge-state dependence of the Ne x-ray spectrum.

2. Very large L x-ray emission yields from the Cl projectile were found to be nearly independent of charge state.

3. Increase of multiple ionization of Ne with increasing Cl ion charge state is observed as a shift in the centroid energy of the Auger electron peak. The charge-state dependence of the total ionization cross section can be accounted for in terms of a decrease in the screening of the projectile nuclear charge.

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1. Permanent address: Hahn-Meitner-Institut, Berlin.
14.10. Recoil Effects on the Impact Parameter Dependence of Inner-Shell Ionization by Heavy Ions

D. Burch

Elastic scattering in heavy-ion collisions can impart a large energy transfer to the recoil target atom. In a study of inner-shell ionization of a target atom B in collisions with a projectile A, careful attention must be paid to the possible ionization cross section in B + B at the typical recoil energies produced. A striking example of this effect has been demonstrated recently. In 200 to 500-keV Ne⁷ + Al, the entire Al K x-ray yield is due to recoil Al + Al collisions. In higher-energy collisions in thin foils the recoil effect on the total cross section is typically much smaller than in this example except, possibly, in cases where the projectile is much heavier than the target. The recoil contribution to the observed ionization probability, however, can be significant even when the effect on the total cross section is negligible: the work reported here was intended to emphasize this point.

Approximate expressions have been derived to estimate the magnitude and scattering angle dependence of the recoil contribution to the ionization probability. The primary assumption is a straight-line trajectory for the recoil atom. The results include an average over the azimuthal dependence of the recoil target thickness for arbitrary recoil and target angles. The approximate results will be tested with an expression provided by Taulbjerg which, based on the same assumptions, reduces the exact expression to a single numerical integration.

A numerical example has been worked out for L-shell ionization in I + Te collisions based on model-dependent and empirical estimates of
the Te + Te cross sections at low energies. It was found that this effect could contribute to the unexpected rise in the probability at small impact parameters observed by Stein et al.\(^3\)

Another "recoil effect" has also been investigated. It has been shown that the decrease in ionization probability at small impact parameters predicted by a molecular promotion model with rotational coupling cannot be unambiguously tested by experiment if the target and projectile are indistinguishable.\(^4\) This result is of interest since this ionization mechanism is unique to symmetric or near-symmetric collisions.

2. K. Taulbjerg, private communication.
15. MEDIUM ENERGY PHYSICS

15.1 Total Pion Nucleus Cross-Sections

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

The existence of both positive and negative pions makes it easier to interpret their total cross-sections with nuclei, than it is for protons. To some approximation the average cross-section, $\frac{1}{2}(\sigma^+ + \sigma^-)$, gives a pion-nucleus cross-section with Coulomb effects removed. In the same sense, the difference ($\sigma^+ - \sigma^-$) is a measure of the Coulomb effects, but if it is measured precisely and systematically one might hope to learn from this quantity differences in the nuclear-force responses of the + and - pions to the nuclei, arising from differences of neutron and proton distributions in nuclei. There have been a few recent reports of measurements of total pion cross-sections in light elements. The excitation functions up to 300 MeV show the presence of the well-known $(3,3)$ resonance. It is observed to become less sharp and to shift to lower incident energy with increasing target mass number in a way that is not yet fully understood.

The main difference between our measurements (the first set of which will be run at LAMFF in May) and earlier ones is that we have cleaner pion beams with intensities that are as much as 100 times larger than had been available. Our choice of targets and incident energies will reflect this improvement. The new emphases will include (1) Runs at low energy (30 to 50 MeV) where little information exists, (2) Runs to study changes in neutron and proton distributions in nuclei due to the addition of new nucleons (for example, comparisons of $^{16}_0$O with $^{18}_0$O, of $^{12}_C$C with $^{13}_C$C and of $^{40}_0$Ca with $^{44}_0$Ca and $^{48}_0$Ca). (3) Runs on some thin targets of high Z. We have accumulated a stock of very pure targets of reasonable thickness and thickness uniformity some of which are listed in Table 15.1-1. We will be able to run no more than a small fraction of these in our first run at LAMFF.

<table>
<thead>
<tr>
<th>(CH$_2$, CH$_2$, a)</th>
<th>a) These will involve a subtraction using a graphite target. The determination of the H cross-section will test the subtraction procedure.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$Be</td>
<td>b) Liquid Helium II in a target of special design (H.O. Meyer).</td>
</tr>
<tr>
<td>$^{9}$Be</td>
<td>c) The H$_2$ $^{18}_0$O has been kindly loaned to us by N. Matviyoff.</td>
</tr>
<tr>
<td>$^{10}$B, $^{11}$B</td>
<td>d) Prepared by E.H. Kobisk.</td>
</tr>
<tr>
<td>$^{12}$C, $^{13}$C</td>
<td>e) We have sheets of many metals with A values spread throughout the periodic table.</td>
</tr>
<tr>
<td>$^{16}$O, $^{18}_0$O</td>
<td>f) Prepared by H. Marshak in connection with his proposal to study this cross-section as a function of nuclear orientation.</td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td></td>
</tr>
<tr>
<td>$^{48}$Ca, $^{44}$Ca, $^{40}$Ca</td>
<td></td>
</tr>
<tr>
<td>Metallic Foils</td>
<td></td>
</tr>
<tr>
<td>$^{15}$Hg</td>
<td></td>
</tr>
</tbody>
</table>

Table 15.1-1. Targets in Hand for Total Pion Cross-Section Measurements.
Fig. 15.1-1. The arrangement of counters for the total pion cross-section measurements. The incident pions (energy 50 to 300 MeV with ±1% resolution) are identified and counted individually by means of the timing counters, the halo counters and the DISC. The transmitted pions are observed in the multiwire chambers and in the "transmission" stack of scintillators. Distances between most components are adjustable along the pion beam axis. The LEP spectrometer magnet system is a vertical arrangement of 4 magnets in a plane at 45° to the proton beam axis. The distance from the pion production target to the experimental target is 14 m.

During the past year the major pieces of experimental equipment have been assembled and tested. Figure 15.1-1 shows the experimental layout as it is presently envisioned. The beam is defined by the two timing counters and the halo veto counter. Muon and electron rejection are provided by the DISC and time-of-flight criteria. Targets and blanks are rotated into place on a target wheel which can be turned remotely from the counting house. The counters for detecting particles passing through the target are a set of wire chamber planes and a stack of scintillation counters subtending a uniform sequence of solid angles at the target. The wire chambers also can be used to reject events where the pions pass the target without interaction, but decay before detection. Last, a small detector for checking the efficiency of the wire chambers and scintillators is
placed at the rear of the apparatus.

During the evaluation of the properties of the pion beam of the Low Energy Pion channel the time-of-flight apparatus, DISC, and halo counters were all tested. Results of the time-of-flight measurements are presented elsewhere. The DISC was shown to give better than 1000:1 pion to muon selection. The halo counters are two counters which match together to form a 7/8" hole surrounded by scintillate, they were found to give quite uniform pulse heights for uniform illumination by pions. The wire chambers have been shown to function adequately in later tests. In short, all of the major components of our apparatus seem to be working. Our first job during the upcoming run will be to get them to work together and to record their events properly with the help of data acquisition programs developed by our collaborators.

* Our collaborators in this work include: (University of Montana) M. Jakobson, D. Jepessen; (Los Alamos Scientific Lab.) D. Hagerman, R. Redwine, H.O. Meyer; (New Mexico State University) G. Burleson, K. Johnson; (Stanford University) J. Calarco.


2. See Sec. 15.2 of this report.

15.2 Time of Flight Measurements at the LAMFP Low Energy Pion Channel

M.D. Cooper and N.G. Ward

The measurement of pion-nucleus total cross sections (LAMFP expt #2) requires the individual identification of incident particles as pions, and to help with this objective a time of flight system using scintillation counters has been built and tested.

The time of flight information will be used in an overlap, coincidence mode capable of giving 1/2 nanosecond resolution at high count rates and some of the methods employed here reflect this application. However, during the LAMFP beam line tuneup last October the low particle fluxes allowed testing via the more conventional time to amplitude converter (TAC). The spectra acquired were of two types; those representing the differing flight times between two counters and those showing the differing flight times from the pion production target to the counter.

The detectors were one inch diameter discs (5 mm and 10 mm thick) of Pilot M scintillators whose cylindrical edges were bonded to six inch long light pipes which illuminated the central square inch of the photocathodes of 56 AVF phototubes.
With the low energy pion channel (LEP) set to select particles of momentum equal to 103 MeV/c, the velocities of pions, muons, and electrons are sufficiently different to allow particle identification by time of flight between two counters about one meter apart. First, the resolution of the counters can be checked by placing a degrader in front of them which stops all particles except relativistic electrons. The timing resolution was 400 psec. Dividing by the \(\sqrt{2}\), the resolution in a single counter is found to be 280 psec. Then, on removing the absorber a time of flight spectrum such as shown in Fig. 15.2-1 is obtained. The calibration is 170 psec/channel. The momentum bite of LEP was 0.2% so that an essentially central trajectory was selected.

The ratio of pions to muons in Fig. 15.2-1 is roughly the same as seen by measuring the channel contamination for a central trajectory with multi-wire chambers and a \(\Delta E-E\) counter telescope. The small part of the beam phase space selected by these small timing counters makes them detect only central trajectory particles.

The angular distribution of muons from the decay of pions has a maximum near the maximum lab angle allowed by the center of mass to lab transformation:

\[
\tan \theta_{\text{max}} = \left[\gamma_n \sqrt{13.68^2 - 1}\right]^{-1} \text{ for } T_\pi > 5.4 \text{ MeV}, \theta_{\text{max}} = 37.9/P_\pi.
\]

Since the maximum angle that a particle can be off axis and pass both timing counters when they are 1 m apart is only 3°, these counters are quite insensitive to decay muons. The observed muon peak has a velocity corresponding to muons with the momenta selected by LEP; these muons probably originate near the production target. Muons formed in the last quadrupoles would appear between the electron and muon peaks shown. Muons formed from decays after passing timing counter two will be a continuum from this point to the pion peak. The observed spectra show little evidence for decay muons produced within the channel which will satisfy the geometric restrictions of the counters.

Fig. 15.2-1. The two counter time of flight spectrum at 103 MeV/c momentum. Clean separation of electrons, muons and pions is obtained with few muons observed which can be attributed to pion decay within the channel. (i.e., most muons are from the production target.) The time calibration is 0.17 ns per channel.
Fig. 15.2-2. A block diagram of the electronics which shows the time pick-off circuitry for both the counters and the 200 MHz signal.

A block diagram for the electronics used to time against the 200 MHz R.F. is shown in Fig. 15.2-2. For the timing between two counters described above, the start and stop signals were from the outputs of the zero crossing discriminators. The circuit referred to as a "differentiator" is a pulse shaping circuit intended to give pulses with 1 nsec rise times so that the zero crossing discriminators would have less sensitivity to noise.

To obtain a usable timing signal from the 200 MHz of the accelerator, it is necessary to work with a subset of the 200 MHz pulses to prevent any device such as the TAC from being required to stop only 5 nsec after it starts. This was accomplished here by a fast coincidence with the timing counters. The coincidence is such that the output has its leading edge determined by the R.F. signal. To minimize the non-linearities due to the rounded edges of the pulses, one must have as fast rising pulses as possible, and in this case that was accomplished through the use of a differentiator. This pulse, which has less than 1 nsec rise and fall times produces a coincidence output which is linear over nearly 4 nsec out of the 5 nsec repetitive period of the signal.

Since any phototube output is in coincidence with some R.F. pulse, the random events from neutrons and gamma rays produce a large background under the particle peaks. This background is greatly reduced relative to the particle events because the small detectors are relatively inefficient for neutrons and gammas. By requiring the logical coincidence with a second counter, this background is nearly eliminated.

A light emitting diode was imbedded in the light pipe of each timing counter. The time jitter of the diodes in each counter was small compared to the time resolution of the counters. By adjusting the variable delay between the diodes to match the actual time that particles took to pass between the
detectors, a high rate of properly timed coincidences was obtained which made setting the above coincidences much easier than it would have been with beam pulses.

Figure 15.2-3 shows the best time resolution spectrum obtained for timing one counter against the R.F. of the accelerator when the channel is set to accept 100 MeV pions with a momentum bite of 1%.

Particle identification done with two thick plastic scintillators showed the beam consisted almost solely of pions with some muons and very few electrons. The time spectrum shows no evidence for an electron peak and unfortunately the flight time for 195 MeV/c muons over a 15 m path is shorter than that for pions of the same momentum by almost exactly 1 R.F. period (5 nsec). Because of the repetitive nature of the R.F. signal the pion and muon peaks are therefore degenerate.

There are three major contributors to the time spread measured in this way. They are the counter time resolution, channel isochronism, and the time spread of the proton bunch at the production target. The overall time spread of the peak in Fig. 15.2-3 is 600 psec.

A single counter's resolution was shown to be about 300 psec and estimates of the isochronism of the channel at 195 MeV/c predict a similarly small contribution to the time resolution. Reducing the momentum acceptance to 0.2% did not affect the resolution. This means that the dominant contribution comes from the primary proton beam. The time spread in the proton bunch is due to the energy resolution of the beam and the length of the flight path from the last R.F. cavity to the production target. Although at 700 to 800 MeV proton energy this spread may be expected to be small, the operating conditions during these measurements were 497 MeV with a flight path of around 375 m. For a beam energy spread of 0.2% FWHM one expects an 840 psec time spread at the production target. This is sufficiently greater than the other sources of time spread to make the width of the peak in Fig. 15.2-3 largely a measure of proton beam time spread. The time width of the peak in Fig. 15.2-3 corresponds to a proton beam energy spread of 0.14% FWHM. Under the usual operating conditions the resolution was closer to 800 psec, but Fig. 15.2-3 represents a particularly stable period of accelerator conditions.
It can be said in summary that particle identification using two counters separated by a flight path or just one counter timed against the R.F. signal will apparently prove to be a practical technique at LAMFP.
16. ENERGY STUDIES

16.1 Energy Sources and Resources

D. Bodansky and F. Schmidt

Early in 1973, when the acute energy crisis was still to come, we began a low-key energy study program. Our initial intent was to acquaint ourselves with the overall picture. Our early concentration was chiefly on resources and facts of nuclear reactor safety.

By summer 1973 we felt ready to draw others into our study program. Accordingly, regular seminars were held at the Laboratory during the summer months. Laboratory staff personnel and graduate students contributed to these seminars by leading discussions on various topics, including total energy resources, radio-activity from nuclear reactors, fuel cells, and power transmission. Subsequent to the summer, our energy related activities have included participation in a campus-wide ad hoc committee on energy (DB), organization of a senior seminar devoted to the energy problem (FHS) and attendance at the energy symposium at the February 1974 American Physical Society meeting in Chicago. The seminar led to a Letter to be published in Physics Today responding critically to the assessment of resources made by J.C. Fisher of the General Electric Company in an article in that journal.

Our attempts to obtain a broad view have led us back to a more extensive study of nuclear fission as an intermediate-term solution to the energy problem. A joint paper is now in preparation stating our views.
17. RESEARCH BY USERS AND VISITORS

17.1 Radioisotope Production for Myocardial Imaging in Nuclear Medicine

Gervas M. Hinn, Wil B. Nelp and William G. Weitkamp

The production of $^{13}$NH$_3$ ($\tau = 10$ min.) and $^{43}$K ($\tau = 22$ h) for heart and myocardial imaging in nuclear medicine is currently being investigated. $^{13}$NH$_3$ has been produced using the reaction $^{16}$O(p,$\alpha$)$^{13}$N. 10.5 MeV protons were used to bombard a water target previously described in connection with $^{18}$F production.\(^1\) Using the water target, a 20 $\mu$A beam for 20 minutes produced 200 mCi of $^{13}$NH (E.O.B.), of which 100 mCi were recovered as $^{13}$NH$_3$ in a volume of 10 ml for use 5 minutes after the end of bombardment. Reduction and distillation were carried out in a standard apparatus used for steam distillation of micro-Kjeldahl digests.

Further improvement in the distillation apparatus should reduce the final volume by a factor of two.

Potassium-$^{43}$ production is still in the stage of feasibility studies. The target is a recirculating Argon gas target with the reaction $^{40}$Ar($\alpha$,p)$^{43}$K being utilized.\(^2\) The $^{42}$MeV $\alpha$ beam of the University of Washington cyclotron will be degraded by one 0.030 mm titanium foil and two 0.10 mm aluminum foils to below 17 MeV. This is necessary to reduce the production of $^{42}$K ($\tau = 12.4$ h) as a contaminant.

It is hoped that enough $^{43}$K will be produced to serve the local medical community.

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17.2 Total Body Neutron Activation Analysis\(^4\)


Measurements of total body calcium by neutron activation ($^{48}$Ca(n,$\gamma$)$^{49}$Ca) have been continued.\(^1,2\) A study of the drug methandrostenolone in the control of postmenopausal osteoporosis was completed. Of the 31 females over 50 years of age who began the study, 16 completed the 2-1/2 year program. The 10 patients on treatment showed an average gain of 2% in total body calcium. The six patients who received a placebo showed an average loss of 3%. The difference between the two groups has a confidence level greater than 99.9%.\(^3\)
A program to determine normal values of total body calcium has been initiated. To date, 12 males and 22 females have been measured, mostly in the 20 to 30 year age group. Average values are 1200 grams of calcium for males and 850 grams for females.

A second method of determining total body calcium by measuring exhaled argon from the reaction $^{40}$Ca(n,α)$^{37}$Ar is under study. Following the animal experiments by Palmer, we have measured $^{37}$Ar excretion rates from 9 patients whose calcium was being measured for other studies. The dominant component in the excretion rate shows a half-life of 20 minutes. Longer lived components are in evidence to the extent that the excretion rate at 7 hours is about 1% of its initial value.

† Work support in part by U.S. Atomic Energy Commission, Grant No. AT(45-1)-2225.

4. $^{37}$Ar studies are supported in part by U.S.N.A.S.A., Grant No. NAS 9-13029.

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17.3A Fast Neutron Beam Radiotherapy - Medical Radiation Physics†

K. Alvar, H. Bichsel, J. Eenmaa, K. Weaver, D. Williams, P. Wootton, and W. Wyckoff

The objective of this project is to develop a well-defined, monitored fast-neutron beam which is suitable for radiotherapy at the University of Washington 60-inch cyclotron. This beam is to be used in clinical comparisions of neutrons and photons as cancer treatment modalities. The first patient was treated at this facility on September 10, 1973. Since that time patient therapy has continued on a routine three-days-per week schedule without interruption.

The neutrons are generated by 40 μA of 21 MeV deuterons incident on a 1.5 mm thick directly water-cooled beryllium target. A diagram of the target assembly is shown in Fig. 17.3A-1. Deuterons leave the target with energies of about 6 MeV and stop in the cooling water or in an aluminum backing plate. The cooling water is untreated tap water flowing in a closed loop at a rate of 20 liters/min. under a pressure of 7 atm., and is initially at room temperature.
The target has operated successfully, without failures, for over 1-1/2 years with deuteron beam currents up to 60 μA.

Measurements of the neutron energy spectrum by proton-recoil and time-of-flight techniques are planned for the near future. Two estimated spectra are shown in Fig. 17.3A-2. The average energy of the neutrons is estimated to be about 8 MeV.

Figure 17.3A-3 shows a layout of the patient treatment area with respect to the cyclotron and beam transport system. The treatment area is located in the cyclotron vault.

The primary radiation barrier consists of a 30 cm thick, 1 m x 1 m square block of iron, followed by a laminated structure of borated water-extended polyester (B/WEP) and steel plate. The total thickness is 70 cm. Neutron beam treatment fields are defined by inter-changeable, rotatable 75 cm-long collimators cast from B/WEP, which fit into a conical-cylindrical stepped aperture in the main barrier. Figure 17.3A-4 shows a cross section of the main barrier and a neutron beam collimator.

Primary neutron beam collimation is comparable with that of super-voltage photon generators. Figure 17.3A-5 shows transverse total dose profiles (normal-
Fig. 17.3A-4. Cross section of therapy shield and collimator.

ized to 100% at the center) for a 10 × 10 cm field at 150 cm SSD (source-skin distance); these were measured in air, and at "zero"-depth in a tissue-equivalent phantom, with a tissue-equivalent ionization chamber. The zero-depth measurement is normalized by a 1.13 backscatter factor with respect to the in-air measurement. These curves show that scatter from the phantom contributes significantly to the dose in the beam penumbra and in the shielded region. Thus it is not expected that addition of more or different shielding material to the primary barrier would reduce the dose to volumes outside of the direct beam.

At large distances from the primary beam axis there is background radiation (with the beam on) producing about 1% of the on-axis dose rate, and composed of scattered neutrons, thermal neutrons and high energy photons. Improvements that may reduce this background are installation of additional shielding and replacement of aluminum and carbon deuteron-beam defining slits and beam stops with structures constructed from tantalum. The latter improvements are intended
Fig. 17.3A-5. Transverse beam profiles measured with a tissue-equivalent ionization chamber.

also to reduce gamma-ray background present after the beam is turned off.

Measurements of neutron-beam parameters essential to patient therapy have been performed. These include measurements, in a tissue-equivalent (TE) phantom, of dose buildup at the surface, backscatter factors, central-axis percentage depth dose distributions, transverse beam profiles, and the $\gamma$-component of the neutron beam.

The maximum-dose buildup depth occurs at 0.2 cm depth. The measured percentage depth dose distributions for a number of field sizes are shown in Fig. 17.3A-6. Backscatter factors for the neutron beam are shown in Fig. 17.3A-7.

Isodose profiles for a 10 x 10 cm...
Fig. 17.3A-8. Neutron beam isodose profiles in TE phantom.

Field in the TE phantom are shown in Fig. 17.3A-8. Profiles such as this are generated from central-axis percentage depth dose distributions and transverse beam profile measurements as a function of depth in a phantom. They can be used to estimate the dose to a tumor volume at depth in tissue.

Studies with a Rossi tissue-equivalent proportional counter (TEPC) are being performed to determine the gamma component of the treatment beam as a function of depth in the phantom. Preliminary results of these measurements are shown in Fig. 17.3A.9.

Measurements of dose attenuation by various materials used for blocking
and/or wedge shaping of the neutron beam have been performed.

Planar dose distributions within a patient can be generated by a computer code (Memorial Hospital external beam treatment planning program, EXTREP). This code is available and is in use at this facility. A wide variety of radiation therapy techniques can be handled, including wedged fields, blocked fields, and any number of stationary fields of different field sizes. Tissue inhomogeneities and patient's curvature can be taken into consideration in the calculations.

For patient positioning for therapy a light beam simulating the treatment field has been provided. An optical distance indicator facilitates the location of the patient relative to the radiation source. Wall-installed laser locating lights are provided to reproduce and monitor the patient's position and orientation for therapy. A chair which can be manually rotated, tilted or translated in three dimensions has been provided for the treatment of head and neck tumors. A patient couch and a kneeling support device are being designed and constructed for other cases. The patient treatment area is in voice contact with the therapy control area by standard intercom and is under constant visual observation via a closed-circuit television monitor.

A therapy control system has been incorporated for monitoring parameters essential to therapy. The relevant parameters monitored are the integrated and instantaneous deuteron beam current on target, the integrated current from a transmission ionization chamber located in the neutron beam between the target and the shield (primary dose monitor), the instantaneous current (dose rate) and its integral (secondary dose monitor) in a redundant transmission chamber in a similar location, and the total elapsed time. A block diagram of the therapy monitoring and control system is shown in Fig. 17.3A-10. For each patient treatment, the relevant dosimetric values are preset with thumbwheel switches prior to the patient's exposure in the beam. Therapy commences when the appropriate switch on the console is depressed, and terminates when the preset dose has been delivered.

The dosimetry monitoring system was designed with the capability of external control by a digital computer. A Raytheon 704 computer system has been installed in the therapy control area for this purpose, for processing patient records, and for off-line computations. The system hardware is currently being debugged.

Two instrument systems have been used for basic neutron-beam dosimetry.
Fig. 17.3A-10. Neutron therapy monitoring and control system.

One system utilizes tissue-equivalent ionization chambers (i.e. wall material of Shonka A-150 tissue-equivalent conducting plastic) with tissue-equivalent (TE) gas filling (64.4% CH₄, 32.4% CO₂, 3.2% N₂), while the other uses tissue-equivalent proportional counters (TEPC) with TE gas filling.

The ionization chambers are calibrated in rads/coulomb for a ⁶⁰Co γ-ray beam whose dose rate calibration is traceable to the National Bureau of Standards. The Bragg-Gray equation is then used to determine the chamber's calibration in rads/coulomb in the neutron beam. The Bragg-Gray equation relates energy deposition to gas ionization, secondary charged-particle stopping power ratios, and W-values. The W-values (i.e. average energy per ion pair) for the neutron beam are derived from a weighted average of the proton (85%) and heavy ion (15%) components of the secondary charged-particle spectra. Stopping powers are taken to be those of protons. Studies are under way to establish more accurate values of stopping powers and W-values for various gases in the ionization chambers. Particular emphasis is being given to the energy dependence of these quantities.

Calculations for the neutron spectrum obtained from 21-MeV deuterons beryllium show that the TE ionization chambers overrespond, i.e. the dose in TE plastic (Shonka A-150) exceeds that in wet-tissue or muscle by 5.7%.
The tissue-equivalent proportional counter (TEPC) is being used to examine, in detail, the spectral composition of the energy lost by secondary charged particles in a small volume of tissue. The TEPC with TE gas filling has been used for an independent determination of the dose and dose-rate, and agreement with the ionization chamber method is to a few percent. The use of the TEPC permits, in addition, an estimation of the $\gamma$-ray contribution to the total dose.

Dosimetry intercomparisons have been conducted with other facilities in the U.S. engaged in fast-neutron cancer therapy. Personnel from Texas A & M and from M.D. Anderson Hospital and Tumor Institute came to our facility in January, 1974 to measure our neutron beam and $^{60}$Co radiotherapy source. Our dosimetry instruments have been calibrated in the neutron beam at the Naval Research Laboratory. Recently personnel from our facility, along with personnel from NRL, traveled to Texas A & M to perform measurements in the TAMVEC neutron beam and a $^{60}$Co $\gamma$-ray source.

These measurements are still being evaluated, but it is already apparent that, for facilities using similar dosimetry systems, relative agreement at the 1% level is possible for neutrons as well as gamma rays.

† Supported by the National Cancer Institute, Grant No. CA 12481-02.
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17.3B Fast Neutron Beam Radiotherapy - Radiation Oncology

Janet S.R. Nelson

Research in the Division of Radiation Oncology is supportive of the Neutron Beam Therapy program which is currently treating cancer patients with neutrons. This research endeavors: (1) to biologically characterize the neutron beam from the University of Washington cyclotron relative to other radiation sources used for cancer treatment, and (2) to do basic radiobiological studies on the difference in tumor response at the cellular level to neutrons relative to X-rays.

The biological beam characterization involves comparison of neutron and X-ray induced damage to a normal animal tissue, the skin of mouse feet and to a malignant neoplasm, the C3HBA mammary tumor of the C3H/HeJ mouse. The relative biological effectiveness (RBE) of neutrons for early skin damage and tumor growth inhibition is given in Table 17.3B-1. Emphasis has been placed on the importance of fractionation schemes in producing significant damage to the tumor with relative sparing of intercurrent normal skin. Work in progress is evaluating additional treatment regimens, as indicated in Table 17.3B-1.

Experiments in progress are investigating C3HBA mammary tumor cell cycle
Table 17.3B-1. RBE\(^1\) for 8 MeV neutrons from the University of Washington cyclotron for various biological effects.

<table>
<thead>
<tr>
<th>Type of Response</th>
<th>Fractionation Scheme</th>
<th>Total X-ray Dose, Rad</th>
<th>RBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early skin damage(^2)</td>
<td>1 fraction</td>
<td>1900</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>2 fractions at 24-hour intervals</td>
<td>1900</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>2 fractions at 96-hour intervals</td>
<td>1900</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>5 fractions at 24-hour intervals</td>
<td>3000</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>2 fractions neutrons + 3 fractions X-rays at 24-hour intervals (n-n-x-x-x)</td>
<td>1900</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>2 fractions neutrons + 3 fractions X-rays at 24-hour intervals (n-n-x-x-x)</td>
<td>2500</td>
<td>2.5</td>
</tr>
<tr>
<td>Tumor growth delay(^3)</td>
<td>1 fraction</td>
<td>1800</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>2 fractions at 24-hour intervals</td>
<td>1800</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>2 fractions at 96-hour intervals</td>
<td>1800</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>5 fractions at 24-hour intervals</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>2 fractions neutrons + 3 fractions X-rays at 24-hour intervals (n-n-x-x-x)</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>2 fractions neutrons + 3 fractions X-rays at 24-hour intervals (n-n-x-x-x)</td>
<td>1800</td>
<td>9.0</td>
</tr>
</tbody>
</table>

\(^*\) Indicates value to be obtained from experiments in progress.

1. RBE (relative biological effectiveness) is defined as the X-ray dose in rads necessary to reach a particular endpoint divided by the neutron dose in rads necessary to reach the same endpoint.
2. Skin damage is scored over the period 7-35 days postirradiation using a numerical scale which assigns increasing values to redness, dry desquamation, moist desquamation, up to complete breakdown of the irradiated skin.
3. Tumor growth delay is defined as the number of days necessary for an irradiated tumor to reach 10X starting volume minus the number of days required for an unirradiated control tumor to reach 10X starting volume. Tumor volumes are calculated from caliper measurements made in three dimensions.
kinetics in tumors regrowing following neutron or X-irradiation. The cell cycle kinetics of a tumor (duration of the intermitotic cycle, the proportion of tumor cells which are involved in cell division, and the rate of cell loss from the tumor due to cell death, migration, etc.) determine the rate of regrowth which, in the C3HBA mammary tumor, is dependent on total dose of radiation received. This information will help determine if some tumors recurring after neutron irradiation grow more slowly than ones recurring after photon irradiation, a possible indication for neutron therapy for some malignancies.

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17.3C Radiobiological Characterization of Radiotherapy Fast Neutron Beam

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

The major objective of this program is to characterize, biologically, the neutron beam produced by the cyclotron. It is particularly important to make certain that the RBE for late damage is no greater than the RBE for acute injury. For this purpose, the LD50/5day of mice following whole-body irradiation was used to measure the sensitivity of the intestinal tract to acute injury. The LD50/90day, following irradiation of a 4 cm segment of the small intestine of mice, was used to assess late damage to this structure. Relative to X-radiation, the fast neutron RBE for late damage (1.9) did not differ significantly from the fast neutron RBE for acute injury (1.8). The mechanism of death following partial intestine irradiation with neutrons or X-rays was associated with bowel obstruction. A neutron dose of 1.2 kilorad delivered to this segment of the small intestine produced 50% mortality within 90 days.

The interval between X-irradiation of the lumbar spinal cord of mice and the onset of hind-quarter paralysis was observed to be inversely related to the amount of radiation administered. Using the length of latent period as an end point, the fast neutron RBE for spinal cord damage as a function of neutron dose was measured. This RBE for spinal cord injury was observed to be close to unity for high neutron doses in the range of 1700 to 4500 rads and appeared to increase at lower neutron doses.

Neutron RBE values for damage to thymus, spleen, white blood cell count, intestinal mucosa and testes of mice following single and fractionated neutron exposures of various magnitude also have been measured. The RBE for damage to intestine increased with decreasing neutron dose whereas the RBE for the other tissues was independent of dose magnitude. RBE did not decrease as a function of depth in tissue equivalent fluid, but did increase with decreasing field size.

* Division of Radiation Biology, Department of Radiology, University of
1. The LD50/5day is the dose lethal to 50% of the animals within 5 days irradiation.

17.3D Fast Neutron Beam Radiotherapy Clinical Program†

H.C. Berry,‡ A.J. Gerdes,‡ R.G. Parker,‡ and M.D. Soronen*†

The ultimate objective of this project is the clinical evaluation of fast neutron beam radiotherapy of cancer in the human. It has been estimated (suit) that approximately 60,000 patients die annually in the United States with problems related to failure of control of cancer at the primary site. Thus, lack of local tumor control, although a less frequent cause of death than metastases, is a major cause of human morbidity and mortality. Failure to control the primary tumor with conventional radiation therapy may result from several factors including a lessened response of hypoxic tumor cells, recovery from sublethal and potentially lethal radiation injury and postirradiation repopulation of tumor cells. Particulate radiations of higher LET than conventional photon radiations are less adversely affected by subphysiologic oxygenation, have comparably higher relative biologic effectiveness (RBE) and may reduce postirradiation cellular recovery. The theoretical potential of fast neutrons and negative pions to increase local cancer control has stimulated a renewed interest in testing these modalities for clinical use. This is the basis for the funding of this study by the National Cancer Institute.

After extensive study and preparation by the faculties in the Divisions of Medical Radiation Physics and Radiation Biology (discussed elsewhere), the first human cancer treatment at the University of Washington cyclotron facility started on September 10, 1973. Since that time, some 31 patients have entered the program, although all have not completed treatment (Table 17.3D-1).

To date, our interest has primarily been in squamous cell carcinomas and melanomas of the head and neck, glioblastomas arising in the brain and Pancoast tumors. Treatment of these tumors has been possible using the fixed horizontal beam with the patient sitting in a specially designed chair.

It is too early to assess results of treatment to date. Nine patients with glioblastoma multiforme have tolerated whole brain irradiation up to 1850 rads (n + γ) in 17 increments over 43 days without difficulty. Survival data are not meaningful.

Sixteen patients with advanced squamous cell carcinomas arising in the head and neck have tolerated doses up to 2200 rads (n + γ). Mucoal reactions have been vigorous. Skin reactions have been mild. There has been no necrosis of bone or cartilage. Although all tumors have responded, at least to some degree, assessment of local control is not possible yet.

Two patients with extensive melanomas have been treated. In the first, the local response was very good.
The patients with Pancoast tumors (3) and breast carcinoma (1) have not completed treatment for various reasons.

The next cancers to be studied will be squamous cell carcinomas of the intrathoracic esophagus. Only about 5-10% of patients with these tumors are "cured" and local control is achieved in less than 50%.

Ultimately, other cancers poorly responsive to conventional treatment, such as extensive squamous cell carcinomas of the cervix and transitional cell carcinomas of the urinary bladder, will be studied. Patients with these tumors as well as esophageal carcinomas will require specially constructed positioning and holding devices to accommodate the fixed horizontal beam. These devices are being designed.

The research program at the University of Washington is an integrated part of a national study which includes the M.D. Anderson Hospital (Houston, Texas), TAMVEC (Texas A & M, College Station, Texas) and the Middle Atlantic Neutron Therapy Association (MANTA -- Naval Research Cyclotron, Washington, D.C.). The clinical studies have been discussed and designed by all participants so that maximum information will be obtained. The United States programs also are closely cooperative with the study at the Hammersmith Hospital, London, England.

At this time, the patient treatment capacity of our program is smaller than any other. However, the proximity of the University of Washington cyclotron and the University Hospital provides unique opportunities such as the investigation of treatment with frequent daily increments (4 per week). Various patterns of treatment application will be studied prior to initiation of national protocols.

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

17.4 Fission Studies on Elements below Polonium

E.T. Neužil

The helium ion-induced fission of the two stable thallium isotopes has been done with 65 MeV, 41 MeV and 31 MeV helium ions. The mass distribution curves obtained have yielded values of $W_{1/2}$ (width at half maximum of the fission fragment mass distribution) of 16 ± 1 amu and 17 ± 1 amu for the 65 MeV helium ion-induced fission, 18 ± 1 amu and 17 ± 1 amu for the 41 MeV helium ion-induced
fission, and $15 \pm 1$ amu and $15 \pm 1$ amu for the 31 MeV helium ion-induced fission of enriched targets of $^{203}$Tl and $^{205}$Tl respectively.

Work is now proceeding on the particle-induced fission of the enriched mercury and tungsten isotopes (with the exception of $^{198}$Hg which is far too expensive to purchase). We have just begun this work but preliminary results do indicate similar trends, as before. The main difficulty here is that we must deal with six major isotopes of mercury and four of tungsten and deduce the fission contribution of each in each isotopic sample bombarded. This is not especially easy since at the present costs of these isotopes only 2 mg samples may be bombarded and we need all six determinations before we can calculate the contribution of each.

† Supported by Atomic Energy Commission Contract No. AT(45-1)-1759.
Department of Chemistry, Western Washington State College, Bellingham, WA.

17.5 Delayed Neutron Spectra from Fast Fission†

G.W. Eccleston, W.R. Sloan, and G.L. Woodruff

The energy spectra of the delayed neutrons associated with fast fission of $^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, and $^{239}$Pu isotopes are to be determined. The University of Washington sixty inch cyclotron will be used to produce the fast source neutrons, approximating a degraded fission spectrum, by focusing an 11 MeV proton beam onto a beryllium target.

The north edge of the cyclotron duct has been modified to incorporate an extension cavity, Fig. 17.5-1, which interfaces a 7.62 cm × 3.81 cm beryllium target and coolant manifold to the vacuum duct. At this location the proton beam occupies a 5 cm × 2.5 cm rectangular area on the target for a focus magnet current setting of 44 amp, up-down magnet current of 1 amp and the focus magnet shim removed. Proton beam currents in excess of 50 μA (meter full scale) have been recorded for this target configuration.

Delayed neutron measurements require sample irradiations followed by a counting cycle with the irradiation source removed. This requirement has been satisfied through an interface allowing a positive logic signal to switch the cyclotron ion source arc voltage on and off. Subsequent measurements have shown proton beam turn-on and turn-off times of approximately 50 msec and 20 msec, respectively.

† Work supported by U.S. Atomic Energy Commission, Contract No. AT(45-1) 2225 TA31.
* Department of Nuclear Engineering, University of Washington.
Fig. 17.5-1. Target-sample-detector configuration at the University of Washington 60-inch cyclotron.

17.6 Calibration of Dielectric Track Recorders

F.H. Ruddy* and G.E? E. Tripard**

The incipient application of negative pion beams to tumor therapy will require some reliable method for quantification of the physical and biological doses received by the patient in order that the pion therapy program can be evaluated. At this time there are several aspects of the basic physical processes that are still imperfectly understood, including the role of heavy ions emitted by both stopped and moving negative pions. As a preliminary study of a proposed project at the Los Alamos Meson Facility we have begun calibration of
cellulose nitrate for particle identification of ions for \( Z \leq 8 \) using oxygen ions from the University of Washington tandem Van de Graaff.

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** Department of Physics, Washington State University, Pullman, WA.

17.7 Alpha Particle Injection into Reactor Materials

K.R. Garr,* D.W. Keefer,* D. Kramer,* M.M. Nakata,* and A.G. Pard*

Injections of alpha particles into fast-reactor cladding and structural alloys are being carried out under a program at Atomics International. This program is sponsored by the AECL-DRRD and is called "Irradiation Damage in Cladding and Core Structural Materials", Task 2, Contract AT (04-3)-824. The injections are carried out with the University of Washington's cyclotron, which provides a convenient method of introducing homogeneous concentrations of alpha particles (helium) at a low temperature into various cladding and structural candidates. Helium implantation is designed to simulate reactor conditions, in which helium is produces by \((n,\alpha)\) reactions.

After implantation, proton irradiations are performed on another accelerator to create displacement damage comparable to that achieved by in-reactor neutron irradiation. As a result of these irradiations, voids (collections of large numbers of irradiation-produced vacancies) are formed in the samples. Void formation is studied as a function of the variables proton flux, proton fluence, irradiation temperature, sample microstructure, and helium concentration. Electron microscopy is used to ascertain the effects of these variables on the size, density, and distribution of the voids.

* Atomics International Division, Rockwell International Corporation, Canoga Park, CA 91304.

17.8 Hyperfine Interaction Constants in the \( 3P_1 \) State of \( ^{111}\text{Cd}^m \) and \( ^{105}\text{Cd} \)

B.D. Geelhood* and M.N. McDermott*

As part of a program to determine the magnetic structure of cadmium nuclei, 49-min \( ^{111}\text{Cd}^m \) and 55-min \( ^{105}\text{Cd} \) were produced by a 3 hour a bombardment of a natural palladium foil at the University of Washington cyclotron. The angular redistribution of 3261 \( \AA \) resonance radiation scattered from a vapor sample of these isotopes, which occurs when an external magnetic field causes two Zeeman sublevels of the \( 3P_1 \) state to cross, was detected by a photomultiplier in a direction perpendicular to both the incoming light and the applied magnetic
Two $\Delta M_p = 2$ level crossings $(F,M_p)(F',M_p-2)$ were observed for each isotope at fields corresponding to proton resonance frequencies in a spherical water sample, presented in Table 17.8-1. These values yield the $3p_1$ hyperfine interaction constants $A(111m) = -1025.43(4)$ MHz, $B(111m) = -104.5(5)$ MHz, $A(105) = -669.302(14)$ MHz, and $B(105) = +207.0(3)$ MHz corrected to second order. These values are considerably more precise than those previously obtained.1

Table 17.8-1. Level crossing frequencies

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Crossing Levels</th>
<th>Proton Resonance Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{111}$Cd$^m$</td>
<td>$(13/2,13/2) \times (11/2,9/2)$</td>
<td>8479.50(17)</td>
</tr>
<tr>
<td>$^{111}$Cd$^m$</td>
<td>$(11/2, 9/2) \times (11/2,5/2)$</td>
<td>8909.0 (17)</td>
</tr>
<tr>
<td>$^{105}$Cd</td>
<td>$(7/2, 7/2) \times (5/2,3/2)$</td>
<td>6236.13(21)</td>
</tr>
<tr>
<td>$^{105}$Cd</td>
<td>$(5/2, 3/2) \times (5/2,-1/2)$</td>
<td>5711.1 (39)</td>
</tr>
</tbody>
</table>

* Department of Physics, University of Washington.

17.9 Radiative Proton Capture by Carbon-12

D. Berghofer, K. Ebisawa, M.D. Hasinoff, B. Lim, D.F. Measday, and T.J. Mullingan

The nitrogen-13 nucleus consists of a single valence proton outside the closed shell carbon-12 core. The simplicity of this structure, together with the information available about the "mirror image" nucleus carbon-13, makes $^{13}$N an attractive subject. This report is a continuation of previous studies done at this laboratory.1,2

In the present work, the ninety degree excitation function for the $^{12}$C$(p,\gamma) ^{13}$N reaction was measured for proton energies from $E_p = 14$ MeV to 24.4 MeV. It was hoped that the $(p, \gamma)$ reaction could act as a "referee" for spin-parity assignments made from other reactions. Particular attention was paid to regions near $T = 3/2$ resonances seen in inelastic reactions. Also detected were the $(p,\gamma_1)$ and $(p,\gamma_{2+3})$ capture gamma-rays, as well as the $12.71$ MeV and $15.11$ MeV gamma-rays from the inelastic reactions, when above threshold. Two angular distributions were taken on the high energy side of the G.D.R., in addition to six angular distributions in the region of the pygmy resonance ($E_p \approx 12$ MeV).

The U.B.C. gamma-ray-spectrometer ($25 \text{ cm} \times 25 \text{ cm NaI}$) was used in this study, with standard pulse shaping techniques. The energy resolution has a
FWHM = 4% for the 15.11 MeV gamma-ray. The line shape for this gamma-ray, adjusted to keep the energy resolution constant, was used to fit all the data including the capture gamma-rays which varied from 11 MeV to 24 MeV.

A typical spectrum is shown in Fig. 17.9-1. At lower proton energies, the $\gamma_1$ and $\gamma_{2+3}$ lines frequently overlap with the $\gamma_{15.11}$ and $\gamma_{12.71}$ lines, and are not well defined. An enriched carbon-12 target was used. The target thickness was measured using the narrow ($\Gamma = 1.3$ keV) $T = 3/2$ resonance in the $(p,\gamma_0)$ reaction at $E_p = 14.231$ MeV and yielded a value of $380 \mu g/cm^2 \pm 12\%$.

![Typical Spectrum](image)

Fig. 17.9-1. Proton capture spectrum on $^{12}$C at 22.4 MeV.

The $\gamma_0$ yield from near threshold to 24.4 MeV is given in Fig. 17.9-2. We estimate the uncertainty in the relative normalization of the different sets of data and in absolute cross-section to be $\pm 25\%$. The main strength of the dipole
Fig. 17.9-2. Excitation function for $^{12}\text{C}(p,\gamma_0)$ to $E_p = 24.4$ MeV.

The resonance is centered at $E_p = 20.5$ MeV and has a width $\Gamma = 3$ MeV. A peak is seen at this energy in the $\gamma_{15,11}$ yield, with a width $\Gamma = 1.5$ MeV. Scott, et al.\(^3\) and Lowe and Watson\(^4\) have assigned this peak $J^m = 5/2^+$ from $(p,p')_{15,11}$ polarization and inelastic scattering cross sections, with $3/2^+$ also allowed. If this same resonance contributes significantly to the $\gamma_0$ yield, as seems likely, an assignment $J^m = 3/2^+$ would be strongly indicated.

There seems to be some fine structure between $E_p = 16.5$ MeV and 18.5 MeV. The narrow peak at 14.23 MeV is the first $T = 3/2$ resonance in $^{13}\text{N}$. The $T = 3/2$ resonances at $E_p = 17.6$ MeV and 18.46 MeV seen in the $\gamma_{15,11}$ yield do not appear in the $\gamma_0$ yield. Whether or not the yield drops at 14 MeV is still a matter of debate.

The peak at 23 MeV seems well defined and had not previously been seen in this reaction. It may correspond to a peak seen at 23 MeV in the

\[ \text{199} \]
Angular distributions of the gamma-rays were measured at the energies $E_p = 22.4$ MeV and 23.2 MeV. Figure 17.9-3 gives the Legendre polynomial coefficients for the $Y_0$ according to the equation:

$$Y(\theta) = A_0 (1 + \sum a_n P_n (\cos \theta))$$

Several fits were forced to be non-negative. The angular distributions of the capture gamma-rays are all strongly asymmetric about 90°, indicating interference between levels of opposite parity. Assuming the G.D.R. has $J^\pi = 3/2^+$, the $Y_0$ angular distributions are consistent with $E1 - E2$ interference with the $J^\pi = 5/2^-$ level at $E_p = 22.4$ MeV seen in the $\gamma_{15.11}$ and $\gamma_{12.71}$ yield curves. Note, however, that this interference could not produce a dip at 22.4 MeV in the ninety degree yield of the $Y_0$. The angular distribution of $\gamma_{15.11}$ at $E_p = 22.4$ MeV is consistent with the level being populated via a compound nuclear state of $J^\pi = 5/2^-$, but the angular distribution at 23.2 MeV is more consistent with a $1/2^+$ or $3/2^+$ state.

The $^{12}_C(p,\gamma)N$ yield in the region of the pygmy resonance was previously measured at this laboratory. The results are also reproduced in Fig. 17.9-2. The most striking features are the two narrow minima at $E_p = 10.62$ MeV and 13.12 MeV, thought to be an interference effect. Angular distributions were measured at energies indicated by arrows. The Legendre coefficients are plotted in Fig. 17.9-3 for fittings to order 2 and to order 4. In general, adding the third and fourth order polynomials did not significantly improve the fit, according to the F test (with the possible exception of the angular distribution at $E_p = 13.5$ MeV). The only dramatic variations occur in the $A_0$ coefficient. This indicates that, if the minima are an interference effect, the resonances involved have the same spin and parity. State having $J^\pi = 3/2^+$ could give a distribution with $a_2 = -0.5$. Experimentally, the $a_2$ values are more negative, and the $a_1$ values are non-zero, which indicates the presence of a broad interfering background, some of which is probably from E2 radiation.

The measured yields for the 12.71 MeV and 15.11 MeV gamma-rays are given in Fig. 17.9-4. These yields are in good agreement with previous results. Most
structure has been previously analyzed. We note only that the peak at $E_p = 16.8$ MeV and the dip at 17.3 MeV in the
$\gamma_{12,7}$ yield can probably be accounted for by the known resonances at $E_p = 15.5$
MeV and 17.3 MeV interfering with a broad background. The structure was fit
as the 17.3 MeV resonance interfering with a broad background. The weak and
strong solutions found correspond to

$$(\text{for } E_p = 17.3 \text{ MeV})$$

$$\Gamma_{p'p'} \approx 2000 \pm 20\% \quad 44000 \pm 30\% \quad (\text{keV})^2$$

One might guess the contribution of the
16.5 MeV resonance to be less than that of the 17.3 MeV resonance.

Our study of this reaction is continuing.

* Department of Physics, University of British Columbia, Vancouver, B.C., Canada.


Rev. 104, 1064 (1956).

see also: Kuan, et al., Nucl. Phys. 80, 509 (1964); Simons, Phys. Rev.
155, 1132 (1967); Patterson, et al., Proc. Phys. Soc. 88, 641 (1966);

17.10 Radiative Proton Capture into the Giant Dipole Resonance of $^{28}_P$

D. Berghofer,*, K. Ebisawa, M. Hasinoff,*, S.T. Lim,*, and D. Measday*.

Our preliminary measurements on the reaction $^{28}\text{Si}(p,\gamma)^{29}_p$ showed a
broad structure (centered at $E_x = 18.0$ MeV), of width approximately 4 MeV, and
significant structure below $E_x = 17$ MeV. Measurement of the $90^\circ$ differential
cross section has continued using an isotopically pure target of thickness

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\( \sim 800 \, \mu g/cm^2 \). The yield curves for the transitions to the ground state \((1/2^+)\)
and to the first excited state \((3/2^+)\) of \(^{29}\text{P}\) have been extracted directly by a
computer program which decomposes the spectrum into mono-energetic gamma-ray
peaks and an underlying background due to either cosmic-rays or pile-up signals.
The mono-energetic gamma line shapes used in the program are either obtained
directly from other reactions or are generated by linear extrapolation from
gamma-ray peaks at nearby energies. Yield curves for \(\gamma_0\) and \(\gamma_1\) are shown in
Fig. 17.10-1 and Fig. 17.10-2 respectively. Fitting errors are also shown for
completeness. A value of \(9.0 \pm 0.5 \, \mu b/\text{sr}\) is obtained for the differential cross
section at \(E_x = 16.0 \, \text{MeV}\). A more precise evaluation of the cross section is in
process.

**Fig. 17.10-1.** Excitation function for \(^{28}\text{Si}(p,\gamma_0)^{29}\text{P}\) taken at \(90^\circ\).

Recent \((\gamma,n)\) measurements\(^2\) show that even-odd nuclei in \(2s-1d\) shell have
very little intermediate structure in the GDR region in comparison with even-even nuclei. The broad structure, centered at \(18.0 \, \text{MeV}\), can then be easily
identified as the electric dipole giant resonance built on the ground state of
\(^{29}\text{P}\). The center of the GDR built on the first excited state of \(^{29}\text{P}\) appears to
be at \(E_x = 20.5 \, \text{MeV}\). The difference of \(2.5 \, \text{MeV}\) between the centers of the GDR's
seem to be much bigger than the excitation energy \((1.38 \, \text{MeV})\) of the first excited
state. It is interesting to note that if a spheroidicity parameter \(\sigma = 0.53\) is
assumed a separation of GDR components, due to deformation, of \(2.40 \, \text{MeV}\) can be
predicted. The yields also show that intermediate structures superposed on the
Fig. 17.10-2. Excitation function for $^{28}\text{Si}(p,\gamma_1)^{29}\text{P}$ taken at $90^\circ$.

Concentrations of E2 and M1 strength below the electric GDR has been postulated for a long time. Recent investigation of 2s-1d nuclei by $180^\circ$ electron scattering show that there is considerable M1 strength below the electric GDR region. The investigation of this lower energy region via the radiative capture reaction has received considerable attention in the past few years. In the present reaction we have obtained more detailed yield curves around 9.56 MeV (Fig. 17.10-1) and 11.20 MeV proton energy. The total widths for these resonances are believed to be less than 15 keV. Angular distribution measurements were obtained at the bombarding energies of 8.78 MeV, 9.56 MeV and 11.205 MeV. Each distribution was fitted with a sum of Legendre polynomials $W(\theta) = 1.0 + \sum_{i=1}^{n} A_i P_i(\cos \theta)$ and the resulting coefficients, shown in Table 17.10-1, will be discussed in the following sections.

As early as 1960 Oda et al. had observed an anomaly at $E_p = 8.78$ MeV in the $^{28}\text{Si}(p,p_{1})^{28}\text{Si}(1.78$ MeV) reaction. The reported total width of 100 keV agrees
Table 17.10-1
Angular Distribution Coefficients of the Legendre Polynomial Fit

\( (W(\theta) \sim 1 + \sum_{i=1}^{l} a_i P_i \cos(\theta)) \) to captures in \( ^{28}\text{Si} \) at several energies.

<table>
<thead>
<tr>
<th>( E_p ) (MeV)</th>
<th>( E_x ) (MeV)</th>
<th>Reaction</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>( a_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.78</td>
<td>11.22</td>
<td>((p,\gamma_0))</td>
<td>0.21</td>
<td>-0.88</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>\pm 0.07</td>
<td>\pm 0.13</td>
<td></td>
</tr>
<tr>
<td>9.56</td>
<td>11.98</td>
<td>((p,\gamma_0))</td>
<td>-0.014</td>
<td>-0.54</td>
<td>-0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>\pm 0.078</td>
<td>\pm 0.11</td>
<td>\pm 0.16</td>
</tr>
<tr>
<td>11.205</td>
<td>13.56</td>
<td>((p,\gamma_0))</td>
<td>0.22</td>
<td>-0.53</td>
<td>-0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>\pm 0.09</td>
<td>\pm 0.12</td>
<td>\pm 0.20</td>
</tr>
<tr>
<td>11.205</td>
<td>13.56</td>
<td>((p,\gamma_1))</td>
<td>0.05</td>
<td>-0.50</td>
<td>-0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>\pm 0.23</td>
<td>\pm 0.28</td>
<td>\pm 0.48</td>
</tr>
</tbody>
</table>

well with our result (see Fig. 17.10-1). Differential cross sections measured at \( \theta_{\text{lab.}} = 42^\circ, 52^\circ, 71^\circ, 90^\circ, 108^\circ, \) and \( 138^\circ \) (Fig. 17.10-3) give a non-vanishing \( a_1 \), which indicates interference from different parity states. The introduction of \( P_3(\cos \theta) \) or \( P_4(\cos \theta) \) terms does not improve the fit to the angular distributions. A negative value of \( a_2 = -0.888 \pm 0.131 \) is a strong indication of a \( j = 3/2 \) to \( j = 1/2 \) transition. The theoretical value for \( a_2 \) in a pure \( j = 3/2 \) to \( j = 1/2 \) decay is \(-0.5.7\) This transition can be mainly an \( E1(3/2^- \to 1/2^+) \) or \( M1(3/2^+ \to 1/2^+) \) transition. The small \( a_1 \) of 0.2 can then be easily explained by a small \((\sim 3\%)\) contribution from opposite parity states. Off resonance angular distributions show asymmetries about 90\(^\circ\). If the background in the yield is mainly due to \( E1 \) radiation, a positive parity can be assigned to this 8.78 MeV state.

Measurements on the \( ^{28}\text{Si}(p,p') \) reaction\(^8,9,10\) reveal intermediate structure of width around 150 keV distribution quite uniformly throughout the excitation functions of different channels. Strong correlation between different channels has been reported.\(^8\) However no narrow structures at \( E_p = 9.56 \) and 11.205 MeV have been reported. Although the \( a_2 \) values extracted from the angular distributions at these energies favor assignments of \( j = 3/2 \) for these states, the significant values obtained for \( a_3 \) indicate that the contribution of \( E2 \) transitions to the measurements may be considerable. A comparison of \( ^{29}\text{P} \) and \( ^{29}\text{Al} \) energy levels indicates these resonances are possibly isobaric analogue states of levels in the parent nucleus, \( ^{29}\text{Al} \).
The study of angular distributions in the GDR region and measurements of the 90° yield curves for $E_p > 18.0$ MeV in finer steps will continue. Ex- tractions of a yield curve for $\gamma_5$ is also in process.


17.11 A Measurement of the Response Function for a $10'' \times 10''$ NaI Crystal

M. HASINOFF* and J.W. POULISSON*

Accurate photonuclear cross sections are required in order to extract the amount of isospin mixing in the GDR from the mirror ($\gamma,p_0$) and ($\gamma,n_0$) decays of self-conjugate nuclei. In addition to all the well-known problems of measuring accurate cross sections in nuclear physics such as target non-uniformity, beam current integration and detector solid angle, the radiative capture reaction presents one further complication - the response function of the NaI gamma-ray detector to a mono-energetic gamma ray is itself not accurately known. This is due to the fact that a high energy gamma ray interacts with matter to produce an electron-positron pair and some of the annihilation photons or bremsstrahlung.
can escape from the detector because of its finite size.

The magnitude of these losses is difficult to determine because most measurements are made with the detector surrounded by paraffin to attenuate the slow neutrons and a plastic scintillator shield is normally used to improve the bare detectors' lineshape.

It has been suggested by Brassard\textsuperscript{1} that the tail events are due to Compton scattering of the incident photons in the paraffin and plastic scintillator in front of the NaI but recent measurements by Suffert\textsuperscript{2} and also by ourselves show this effect to be small.

One of the main reasons the tail of the response function is poorly known is that the mono-energetic gamma-ray peak shape can usually be determined only to one-half its energy because of background created by neutron capture gamma-rays. Thus an unknown extrapolation of the tail must be made down to zero gamma-ray energy. This extrapolation is usually made with the help of Monte Carlo calculations. Such calculations agree reasonably well with the low energy gamma spectra ($E_\gamma < 4$ MeV) in small NaI crystals ($3'' \times 3''$ or $5'' \times 6''$) but the situation for 15-30 MeV gamma rays in larger crystals ($10'' \times 10''$) is less certain.\textsuperscript{3}

It was the purpose of the present work to attempt to measure the tail of the response function by detecting the 15.1 MeV $\gamma$-ray produced in the $^{12}\text{C}(p,p'\gamma)$ reaction in coincidence with the low energy inelastic protons feeding the 15.1 MeV level. A natural carbon target (1.4 mg/cm$^2$ thick) was bombarded by 19.5 MeV protons and the scattered protons were detected at 160$^\circ$ in a 3000$\mu$ Si(Li) detector while the $\gamma$-rays were detected at 90$^\circ$ in a 10$''$ $\times$ 10$''$ NaI spectrometer. Coincident and random events ($2\gamma = 25$ nsec) were stored in separate analyzer subgroups for later subtraction of background.

Figure 17.11-1 shows the spectrum of gamma rays in coincidence with the protons feeding the 15.1 MeV level in $^{12}\text{C}$. The solid line is a Monte Carlo calculation\textsuperscript{4} which follows each gamma-ray shower through the NaI crystal. This program attempts to duplicate the experimental situation exactly by allowing the incident $\gamma$-rays to enter the crystal at any angle consistent with the experimental solid angle. Since the Monte Carlo calculation does not include any features of lineshape improvement by the plastic anti-coincidence shield which rejects those events in which the incident gamma ray deposits less than its full energy in the NaI crystal, the data plotted is the "raw" NaI gamma spectrum, corrected for random coincidences.

The 15.11 MeV gamma ray appears in Channel 107 with a full width half maximum (FWHM) of 5.6$. The Monte Carlo calculation has been broadened to the same FWHM and normalized to the photo peak over channels 100-115. The weak peaks in channels 53 and 50 correspond to gamma rays of 7.48 and 7.0 MeV which result from the small branch of the 15.1 MeV level to the second excited state of $^{12}\text{C}$ at 7.65 MeV. Both the full energy and the first escape peaks appear in the spectrum since there is no anti-coincidence rejection being used. The strength of these peaks is consistent with the 2.6% branching ratio determined in Ref. 5.
The tail of the 15.1 MeV gamma ray falls exponentially until obscured by the 7.5 MeV peak in channel 53. Below channel 35 the data are statistically insignificant because of the large background subtraction for the 4.4 MeV gamma ray. The present data do not clearly determine whether the spectrum flattens out below 6.5 MeV or whether it continues to fall exponentially. A flat spectrum between 5 and 7.0 MeV was measured for a 5" x 5" NaI by Alburger and Wilkinson.5 A remeasurement of the present reaction at a higher bombarding energy with better energy and time resolution for the proton detector and a lower counting rate in both the proton and gamma counters should enable us to reduce the contribution of the 4.4 MeV gamma rays and pileup gamma rays to this region of the tail.

It should be immediately apparent that the Monte Carlo spectrum falls considerably below the data between channels 55-100 (about a factor of 5), although it does reproduce the exponential shape of the tail of the experimental spectrum.

Table 17.11-1 summarizes the results obtained for the experimental and calculated lineshapes. The Monte Carlo simulation is seen to provide a rather poor fit to the experimental data especially in the tail region. The experimental spectrum contains 46-50% of the total events below channel 100 whereas the Monte Carlo spectrum contains only 26% of the total events in this region. These disagreements point to the need for further refinement of the Monte Carlo calculation such as the inclusion of photonuclear absorption of the gammas inside the NaI crystal itself and a calculation of the light losses inside the scintillator. The inclusion of such processes into our present program is presently being studied.

If the experimental spectrum is assumed to be correct down to channel 60 we note that the fraction of all events which occur below this point varies from 7.8% to 13% when one considers the two extreme extrapolations:

i) an exponential extrapolation to zero counts in channel 0,
ii) a horizontal extrapolation of 33 counts down to channel 0.

Thus uncertainties in the experimental lineshape should contribute no more than a 7% uncertainty to the error in photonuclear cross sections. Further measurements are planned to determine the tail down to 4.5 MeV which should
allow us to reduce the error on the lineshape to about ±2\%.

Table 17.11-1. Comparison of Experimental and Calculated Lineshapes

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summed Counts Ch. 100-120</td>
<td>6945</td>
<td>6945</td>
</tr>
<tr>
<td>Summed Counts Ch. 60-99</td>
<td>4803</td>
<td>2250</td>
</tr>
<tr>
<td>Summed Counts Ch. 1-59</td>
<td>1000i</td>
<td>2000ii</td>
</tr>
<tr>
<td></td>
<td>132</td>
<td></td>
</tr>
</tbody>
</table>

\[ R_1 = \frac{S(60-99)}{S(100-120)} \]

\[ R_2 = \frac{S(1-59)}{S(100-120)} \]

\[ R_3 = \frac{S(1-99)}{S(100-120)} \]

(i) Tail is extrapolated exponentially to zero counts in channel 0. The fraction of all events which occur below channel 60 is 7.8\%.

(ii) Tail is extended horizontally at 33 counts down to channel 0. This most extreme extrapolation places almost 15\% of the total events in this region which in turn gives an overall uncertainty of < 7\% in the experimental lineshape.

\[ S \]

Department of Physics, University of British Columbia, Vancouver, B.C., Canada.

4. This program is a modified version of the program obtained from the Stanford group by R.L. Ford which in turn is based on a Monte Carlo code by H. Nagel (Z. Physik 186, 319 (1965).
18. APPENDIX

18.1 Nuclear Physics Laboratory Personnel

Faculty

Eric G. Adelberger, Associate Professor
John S. Blair, Professor
David Bodansky, Professor
John G. Cramer, 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
Geirr Sletten, Senior Research Associate
Kurt A. Snover, Senior Research Associate
James W. Tape, Research Associate
Thomas A. Trainor, Research Associate
Michael S. Zisman, Research Associate

Laboratory Supervisory Personnel

Harold Fauska, 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 P. Baker
Douglas R. Brown
John E. Bussoletti
David Chamberlin
Yuen-Dat Chan
Bernardo D. Guengo
Katsuyuki Ebisawa
Robert H. Heffner
William A. Jacobs
David L. Johnson
Kwok-Leung Liu
Roscoe E. Marrs
K. Gopinathan Nair
Dennis L. Oberg
William O. Sumner
Herbert F. Swanson
Howard E. Wieman
Research Assistants

Chemistry

William B. Ingalls
Michael Webb

Physics

Norman L. Back
James C. Wiborg

Full-Time Technical Staff

Professional Staff

Noel R. Cheney, Computer Systems Engineer
Shirley Kellenbarger, Chemist, Detector Maker
Gary W. Roth, Physicist
Rod E. Stowell, Electronics Engineer

Accelerator Technicians

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

Accelerator Operator

Barbara L. Lewellen

Design and Drafting

Peggy Douglass, Graphics Illustrator
Lewis E. Page, Designer

Electronics Technicians

Laverne H. Dunning
Norman G. Ward

Instrument Makers

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, Secretary
Helene G. Turner, Administrative Secretary

Part Time Technical Staff

Ronald Aley
Lawrence S. Baker
Jeffrey Dunham
Lila Graham
David Hall
John Harris
Richard Methot, Jr.

Juan Ochoa
David D. Palmer
Ron Pankiewicz
Hung C. Fon
Brian Popp
Mojtaba Rezvani
Thomas Stewart
Frederick Weiss

1. On leave from the Department of Physics.
2. Now at the University of Rochester, Rochester, New York.
3. Now at the Niels Bohr Institute, Copenhagen, Denmark.
4. Now at the University of Illinois, Urbana, Illinois.
5. Completed degree requirements.
6. Now at the Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
7. Now at the University of North Carolina, Chapel Hill, North Carolina.
9. Now at Texas A & M University, College Station, Texas.
10. Now at the State University of New York at Stony Brook, Stony Brook, NY.
11. Retired.
12. Transferred to the Department of Physics.
13. Terminated.

18.2 Advanced Degrees Granted, Academic Year 1973-1974

David D. Chamberlin: Ph.D. "Electromagnetic Decay of the 7.65-MeV and 9.64-MeV States of \(^{12}\text{C}\)"

Robert H. Heffner: Ph.D. "Experimental Study of the Deformation of the Fission Isomer in \(^{238}\text{U}\)"

William B. Ingalls: M.S. "K-Shell Ionization of Pb in Collisions with C\(^{+}\) Ions of Incident Energies from 30-100 MeV"

William W. Jacobs: Ph.D. "Production of Lithium and Boron Isotopes in Low Energy Proton and Alpha Particle Bombardment of Nitrogen"

David L. Johnson: Ph.D. "A Study of the Mechanism of the Radiative Capture of Low Energy Nucleons by \(^{12}\text{C}\)"

Gopinathan K. Nair: Ph.D. "Nucleon Transfer with Oxygen Ions Below and Near the Coulomb Barrier"

Phyllis A. Russo: Ph.D. "Gamma Branch of the \(^{238}\text{U}\) Shape Isomer"
18.3 List of Publications

Publications Since the 1973 Report:


"Microscopic Analysis of the $^6\text{Li}^6\text{Li}, ^6\text{Li}^*(3.56)^6\text{Li}^*(3.56)$ and the $^6\text{Li}(^6\text{Li}, ^6\text{He})^6\text{Be}$ Reactions", W.R. Wharton, Phys. Rev. 96, 164 (1974).

"Study of the $^6\text{Li}(^6\text{Li}, ^6\text{Li}^*(3.56)^6\text{Li}^*$ and the $^6\text{Li}(^6\text{Li}, ^6\text{He})^6\text{Be}$ Reactions", W.R. Wharton, J.G. Cramer, J.R. Calarco, and K.G. Nair, Phys. Rev. C9, 156 (1974).


Other Publications by Members of the Laboratory:


"The Tensor Analyzing Power Azz at $\theta = 0^\circ$ for the $^3$He(d,p)$^4$He Reaction", T.A. Trainor, T.R. Clegg, and P.W. Lisowski (T.U.N.L.), Nucl. Phys. (to be published).

Papers Submitted or in Press:


"Entrance Channel Effects on the $^{32}$S System: Comparison of $^{12}$C + $^{20}$Ne and $^{16}$O + $^{16}$O Elastic Scattering", (submitted to the International Conference on Reactions between Complex Nuclei, Nashville, June 10-14, 1974).


Abstracts, Talks and Short Conference Papers:


"Auger Spectra Produced in 50- to 600-keV \(^{20}\text{Ne}^+ + \text{Ne}^0\) Collisions", N. Stolterfoht, D. Burch, and D. Schneider, VIII ICPEAC Abstracts, edited by B.C. Čobić and M.V. Kurepa (Institute of Physics, Belgrade, 1973), p. 731.


"High-Resolution Auger Spectra of Ne, Ar, and Kr Excited by 30- to 60-MeV \(^{32}\text{Cl}^+\) and \(^{35}\text{Cl}^+\) Ions", D. Schneider, N. Stolterfoht, D. Burch, H. Wieman, and J.S. Risley, Proceedings of the German Physical Society meeting of March 6, 1974.

"K-Shell Ionization of \(^{12}\text{C}^0\) and \(^{16}\text{O}^0\) by 30- to 60- MeV \(^{32}\text{Cl}^+\) and \(^{35}\text{Cl}^+\) Ions", N. Stolterfoht, D. Schneider, D. Burch, H. Wieman, and J.S. Risley, Proceedings of the German Physical Society meeting of March 6, 1974.


