Gamma Radiation from the Medium Energy Proton Bombardment of Lithium, Beryllium, Boron, Carbon and Nitrogen

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Abstract. Measurements are presented of the gamma radiation produced when lithium, beryllium, boron, carbon and nitrogen are bombarded with 150 mev protons, and the results are discussed with reference to the information they provide about the structure of the nuclei involved. The results include measurements of the residual states produced in (p, 2p) and (p, pn) reactions, which are, to a first approximation, measurements of the parentage of the ground state of the bombarded nucleus. These results are not consistent with a simple $jj$-coupling model of these nuclei and in one case where calculations are available, are consistent with an intermediate coupling model. It is shown that inelastic scattering cross sections are determined by the same matrix element as radiative transitions so that inelastic scattering is a powerful tool for picking out strong radiative transitions to nuclear ground states.

§ 1. INTRODUCTION

In recent years many measurements have been made on the outgoing charged particles from nuclear reactions induced by protons of 100–200 mev. In particular, studies of (p, p') (Strauch and Titus 1956 a, b, Dickson and Salter 1957, Tyrén and Maris 1957a, b, 1958) and (p, 2p) reactions (Tyrén, Hillman and Maris 1958, Gooding and Pugh 1960) cast much light on nuclear structure problems. In the work described in this paper measurements have been made of the yield of gamma radiation from excited states of residual nuclei produced in the bombardment of p-shell nuclei with 140 mev protons. This work complements the charged particle results by providing what are, in effect, measurements with better energy resolution than is possible by observing charged particles alone. In particular, it is possible to make measurements of the fine structure of the pronounced peaks seen in the excitation spectra of residual nuclei in (p, 2p) reactions (Tyrén, Hillman and Maris 1958, Gooding and Pugh 1960) and in the mirror (p, pn) reactions.

§ 2. EXPERIMENTAL METHODS

A proton beam of energy 153 mev from the Harwell synchrocyclotron is focused by quadrupole magnets on to a target at approximately 17 metres from the cyclotron. The protons travel in vacuum up to a point about 50 cm in...
front of the target. A beam intensity (time average) of 1 to $3 \times 10^5$ protons/sec has been found adequate for this work (the duty ratio being approximately 2%).

The beam is monitored by a thin ionization chamber placed 50 cm in front of the target; this monitor is calibrated by comparing measurements of the production of $^{11}$C (Crandall et al. 1956) and the elastic scattering of protons from $^{12}$C at forward angles (Dickson and Salter 1957) with the known cross sections; these two normalizations agreed.

The targets were usually about 20 or 40 MeV thick and were normally of natural isotopic abundance. We were fortunately also able to borrow targets of separated $^6$Li and $^{10}$B. These enabled us not only to make measurements on these isotopes but also to correct the results for natural lithium and natural boron to obtain the cross sections for $^7$Li and $^{11}$B. For a $^{14}$N target liquid nitrogen was contained, for different runs, in a 'Styrofoam' box and in a vacuum-jacketed target. The small concentrations of $^{13}$C in carbon and $^{15}$N in nitrogen were ignored.

The gamma-ray counter was a thallium-activated sodium iodide crystal, 12.5 cm in diameter and 15 cm long, viewed by an EMI photomultiplier type 9530 run at 900 volts. The pulses produced were transmitted by a cathode follower through fifty yards of cable to the counting room where they were amplified and displayed on a hundred-channel pulse-height analyser, which was gated to count only during the cyclotron beam pulse. With this system there was no evidence for any appreciable gain shift due to counting rate: this was checked both by observing the same gamma ray at different beam intensities, and also by comparing the 4.43 MeV gamma ray from the $^{12}$C(p, p') reaction and a much lower counting rate from a polonium-beryllium source. Thus it was possible to use calibration sources ($^{22}$Na, radiothorium, polonium-beryllium) in between runs to identify the observed gamma rays. In every case the energy corresponding to the experimental peak (determined with an accuracy ranging from $\pm 1\%$ to $\pm 5\%$ depending on how well the peak stands out from the background) agreed with the energy of a gamma ray that would be expected from the reaction under study.

The gamma-ray counter was shielded by 10 cm of lead on all sides except towards the target and there was approximately 4 m of concrete between the counter and the cyclotron. With this shielding, the background with no target was between one-quarter and one-tenth, depending on the pulse height, of the counting rate due to the target; this background was smooth with no indication of any peaks. The spectrum due to a target was made up of peaks due to gamma rays superimposed on a smooth background due presumably to neutrons produced in the target. The yield of a gamma ray was obtained by continuing the smooth background under the peak so that the residual gamma-ray spectrum had the proper shape, as determined by comparison with gamma rays from calibration sources. The counter efficiency was then obtained from calculated tables (Miller, Reynolds and Snow 1958) and the cross section for production of the gamma ray calculated. In the case of the $^{11}$B(p, p') reaction where our cross section can be compared with those obtained by integrating proton angular distributions (adjusted to our energy by assuming the differential cross section to vary as a function of $\theta E^2$, $E$ being the kinetic energy of the incident proton) the agreement is excellent.

† The $^{10}$B was lent by Mr. B. Rose of the Atomic Energy Research Establishment, Harwell, and the sample containing $^6$Li was lent by Mr. P. A. White of the Atomic Weapons Research Establishment, Aldermaston.
One has to be careful that the peaks observed are due to gamma rays produced in the target and not due to neutrons interacting in the crystal or in surrounding material. This was checked by inserting lead between the target and the crystal. All peaks at 0.7 MeV and above were attenuated suitably and are thus ascribed to gamma rays produced in the target. Below that energy peaks at about 0.45 and 0.63 MeV were produced by all targets and were found not to be attenuated by the inserted lead. Thus it is impossible to study gamma radiation of less than 0.7 MeV in this work.

§ 3. Gamma-ray Data

A list of gamma rays observed is given in Table 1 with assignments to nuclear transitions and observed cross sections (the information on nuclear energy levels is taken from Ajzenberg-Selove and Lauritsen 1959). Upper limits on the cross section for producing a few gamma rays of particular interest are quoted; these gamma rays were not observed in this work and the upper limit quoted refers to an intensity which would have been evident. Pulse-height spectra corresponding to the gamma rays observed are shown in the figures listed in Table 1. In all cases measurements were made at both 90° and 135° with respect to the proton beam: no evidence was seen for any departure from isotropy of the order of magnitude of the errors quoted on the cross sections. The errors are largely due to the uncertainties in subtracting backgrounds.

In the cases of gamma-ray transitions between states in 10B and 14N, both cascades and cross-over transitions are involved. The feeding of states to produce the observed gamma-ray intensities are given in Table 2 for 10B and Table 3 for 14N. For some entries no positive result is recorded: these cross sections were taken to be zero in calculating the remainder.

As will be seen from Figs 5 and 6, the gamma-ray spectra from bombardment of 14C are rather complicated in three energy regions. The energy of the peak at 2 MeV is found to be 2.00 ± 0.02 MeV. This accuracy was obtained by using the 4.43 MeV gamma ray from inelastic scattering on the same run as a calibration; in this way there could be no question of a gain shift between run and calibration. Thus the strongest gamma ray present in the 2 MeV region is the transition from the first excited state of 11C at 1.99 MeV. However the peak is asymmetric, the asymmetry being consistent with the presence of gamma rays of 2.13 MeV from the first excited state of 11B and 2.15 MeV from the state of that energy in 10B. Using the spectrum shapes of known gamma rays we find the ratio of intensities of 2.13 plus 2.15 MeV to 1.99 MeV to be 0.40 ± 0.05. Taking the cross section for the 2.15 MeV gamma ray to be 0.3 ± 0.18 mbn (see Table 2) we find the cross section for production of the first excited state of 11B to be 0.8 ± 0.3 mbn and for production of the first excited state of 11C to be 2.8 ± 0.4 mbn, a ratio of 0.29 ± 0.13.

The spectrum corresponding to the 4.43 MeV gamma ray from inelastic scattering in 12C is very evident in Figs 5 and 6. However there is definite evidence for the presence of higher energy gamma rays around 4.85 MeV. That this higher energy tail is not due to pile-up or some similar experimental effect is seen by comparing the 12C spectrum with that due to a 4.43 MeV gamma ray produced in the bombardment of 14N shown in Fig. 8, where the high energy side of the 4.43 MeV spectrum falls steeply and continuously to the background. These data were taken under the same conditions with the same counting rate. The intensity of the 4.43 MeV gamma ray from carbon has been estimated from
Table 1. Gamma Rays Observed, with Assignments and Cross Sections

<table>
<thead>
<tr>
<th></th>
<th>(1) Target nucleus;</th>
<th>(2) mean proton energy (%lev);</th>
<th>(3) gamma-ray energy (MeV);</th>
<th>(4) assignment;</th>
<th>(5) cross section (mbn);</th>
<th>(6) figure number</th>
</tr>
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<tbody>
<tr>
<td>$^6\text{Li}$</td>
<td>149</td>
<td>3.56</td>
<td>$^6\text{Li}$</td>
<td>3.56</td>
<td>0.7±0.3</td>
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<td>$^7\text{Li}$</td>
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<tr>
<td>$^9\text{Be}$</td>
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<td>$^8\text{Li}$</td>
<td>0.98</td>
<td>2.4±0.4</td>
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<td>$^{10}\text{B}$</td>
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<td>0.72</td>
<td>$^{10}\text{B}$</td>
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<td>1.8±0.9</td>
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<td>1.0±0.3</td>
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</tr>
<tr>
<td></td>
<td>148</td>
<td>1.43</td>
<td>$^{10}\text{B}$</td>
<td>2.15-0.72</td>
<td>0.7±0.3</td>
<td>2</td>
</tr>
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<td>$^{10}\text{B}$</td>
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<td>0.7±0.4</td>
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<tr>
<td>$^{11}\text{B}$</td>
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<td>0.72</td>
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<td>0.3±0.6</td>
<td>-</td>
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<td>0.8±0.1</td>
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<tr>
<td></td>
<td>148</td>
<td>1.43</td>
<td>$^{11}\text{B}$</td>
<td>2.15-0.72</td>
<td>0.9±0.3</td>
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</tr>
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<td>$^{12}\text{C}$</td>
<td>133</td>
<td>0.72</td>
<td>$^{11}\text{B}$</td>
<td>6.76, 6.81</td>
<td>0.3±0.7</td>
<td>-</td>
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<td>133</td>
<td>1.02</td>
<td>$^{11}\text{B}$</td>
<td>6.76</td>
<td>4.5±0.5</td>
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<td></td>
<td>133</td>
<td>1.43</td>
<td>$^{11}\text{B}$</td>
<td>6.81</td>
<td>1.8±0.2</td>
<td>4</td>
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<tr>
<td></td>
<td>143</td>
<td>1.99</td>
<td>$^{11}\text{B}$</td>
<td>6.76</td>
<td>0.6±0.3</td>
<td>4.5</td>
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<td>143</td>
<td>2.13</td>
<td>$^{11}\text{B}$</td>
<td>6.81</td>
<td>1.0±0.4</td>
<td>5.6</td>
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<td>5.6</td>
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<td>$^{12}\text{C}$</td>
<td>4.43</td>
<td>6.6±1.0</td>
<td>5.6</td>
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<tr>
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<td>4.85</td>
<td>$^{12}\text{C}$</td>
<td>4.46</td>
<td>2.3±1.0</td>
<td>5.6</td>
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<td>143</td>
<td>6.5±0.3</td>
<td>$^{11}\text{C}$</td>
<td>6.50, 6.77</td>
<td>2.1±0.7</td>
<td>6</td>
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<td>151</td>
<td>$^{12}\text{C}$</td>
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<td>0.1±0.1</td>
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<tr>
<td></td>
<td>120</td>
<td>0.72</td>
<td>$^{10}\text{B}$</td>
<td>0.72</td>
<td>3.0±0.5</td>
<td>-</td>
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<tr>
<td></td>
<td>120</td>
<td>1.02</td>
<td>$^{10}\text{B}$</td>
<td>1.74-0.72</td>
<td>1.0±0.2</td>
<td>7</td>
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<tr>
<td></td>
<td>120</td>
<td>1.6</td>
<td>$^{14}\text{N}$</td>
<td>3.95-2.31</td>
<td>0.4±0.1</td>
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<tr>
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<td>120</td>
<td>2.15</td>
<td>$^{11}\text{C}$</td>
<td>1.99</td>
<td>2.1±0.7</td>
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<td></td>
<td>120</td>
<td>2.15</td>
<td>$^{14}\text{N}$</td>
<td>2.13</td>
<td>0.6±0.2</td>
<td>7</td>
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<tr>
<td></td>
<td>120</td>
<td>3.09</td>
<td>$^{13}\text{C}$</td>
<td>3.09</td>
<td>&lt;0.5</td>
<td>8</td>
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<td>120</td>
<td>3.68</td>
<td>$^{14}\text{C}$</td>
<td>3.68</td>
<td>1±6</td>
<td>8</td>
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<td>120</td>
<td>4.43</td>
<td>$^{14}\text{C}$</td>
<td>4.43</td>
<td>20±5</td>
<td>8</td>
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</table>

(1) Target nucleus; (2) mean proton energy (%lev); (3) gamma-ray energy (MeV); (4) assignment; (5) cross section (mbn); (6) figure number.

the height of the steep fall-off on the high energy side. On then subtracting the spectrum due to this gamma ray the remainder was found to correspond to a gamma ray or gamma rays of about 4.85 MeV; it is ascribed to transitions from the 4.75 MeV state of $^{11}\text{C}$ and the 5.03 MeV state of $^{11}\text{B}$. The 4.43 MeV spectrum presumably also contains counts due to a 4.25 MeV gamma ray in $^{11}\text{C}$ and a 4.46 MeV gamma ray in $^{11}\text{B}$, our cross section of $6.6\pm0.3$ mbn for 4.4 MeV gamma rays is higher than those found by integrating angular distributions from the $^{14}\text{C}(p,p')$ reaction. Such cross sections, adjusted to our energy, are 5.0 mbn (Dickson and Salter 1957) and 4.8 mbn (Garron et al. 1960). Experiments are in progress.
Gamma Radiation from Medium Energy Proton Bombardment

Fig. 1. Pulse-height spectra corresponding to γ-rays of energy 3.56 MeV from proton bombardment of natural lithium.

Fig. 2. Pulse-height spectra corresponding to γ-rays of energies 0.72 to 1.43 MeV from proton bombardment of $^{10}$B.

Fig. 3. Pulse-height spectra corresponding to γ-rays of energies 0.72 to 1.43 MeV from proton bombardment of natural boron.

Fig. 4. Pulse-height spectra corresponding to γ-rays of energies 0.72 to 2.13 MeV from proton bombardment of natural carbon.

Fig. 5. Pulse-height spectra corresponding to γ-rays of energies 1.99 to 5.03 MeV from proton bombardment of natural carbon.

Fig. 6. Pulse-height spectra corresponding to γ-rays of energies 2.86 to 6.8 MeV from proton bombardment of natural carbon.
Fig. 7. Pulse-height spectra corresponding to γ-rays of energies 1.02 to 2.31 MeV from proton bombardment of natural nitrogen

Fig. 8. Pulse-height spectra corresponding to γ-rays of energies 3.09 to 4.43 MeV from proton bombardment of natural nitrogen

to measure the individual yields of these gamma rays by observing coincidences between low energy protons and gamma rays produced in both proton and neutron bombardment of carbon. The broad peak at 6.5 MeV is presumably due to transitions from states of $^{11}$C at 6.50 and 6.77 MeV and from states of $^{11}$B at 6.76 and 6.81 MeV. There may be a small contribution from $^{16}$O impurity in the target, as this produces a spectrum peaked at about 6.1 MeV with a cross section of about 30 mbn, due to the (p, pn) and (p, 2p) reactions (A. B. Clegg, P. S. Fisher, K. J. Foley, D. J. Rowe and G. L. Salmon 1960, unpublished work); however

Table 2. Cross Sections (mbn) for Feeding States in $^{10}$B in Various Reactions

<table>
<thead>
<tr>
<th>State in $^{10}$B (MeV)</th>
<th>$^{10}$B + p</th>
<th>$^{11}$B + p</th>
<th>$^{12}$C + p</th>
<th>$^{14}$N + p</th>
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<tbody>
<tr>
<td>3.58</td>
<td>2.1 ± 0.65</td>
<td>7.3 ± 1.5</td>
<td>1.5 ± 0.7</td>
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<tr>
<td>2.15</td>
<td>0 ± 0.4</td>
<td>5.6 ± 1.1</td>
<td>1.5 ± 0.3</td>
<td>1 ± 0.2</td>
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<tr>
<td>1.74</td>
<td>0 ± 1.1</td>
<td>1 ± 1.0</td>
<td>1 ± 0.55</td>
<td>2 ± 0.55</td>
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</table>

Table 3. Cross Section for Feeding States in $^{14}$N(p, p') Reaction

<table>
<thead>
<tr>
<th>State (MeV)</th>
<th>Cross section (mbn)</th>
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<tr>
<td>2.31</td>
<td>0.2 ± 0.22</td>
</tr>
<tr>
<td>3.95</td>
<td>0.4 ± 0.1</td>
</tr>
</tbody>
</table>

the bulk of the peak in Fig. 6 is above this energy and is thus due to $^{12}$C. Our limit of 0.1 mbn for the production of a 15.1 MeV gamma ray is consistent with the result of 0.06 mbn found at this energy by Waddell (1957) but inconsistent with the result of 1.8 mbn of Garron et al. (1960).

The inelastic scattering from the 4.46 MeV state of $^{11}$B has been studied by Tyrén and Maris (1958). Integrating their angular distribution, and adjusting to our energy, we find 3.7 mbn in excellent agreement with our result of 3.8 ± 0.6 mbn.

An excitation function of the 4.43 MeV gamma ray produced in the bombardment of $^{14}$N has been measured, the proton energy being degraded by carbon absorbers placed approximately 30 cm in front of the target and well shielded from the gamma-ray counter by lead. The relative cross sections are given in Table 4, accurate to ±10%.
Gamma Radiation from Medium Energy Proton Bombardment

Table 4. Relative Cross Sections for Production of 4.43 Mev Gamma Ray in $^{14}$N + p Reaction

<table>
<thead>
<tr>
<th>Mean proton energy (MeV)</th>
<th>Relative cross section</th>
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<tr>
<td>85</td>
<td>1.3</td>
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<tr>
<td>105</td>
<td>1.2</td>
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<tr>
<td>125</td>
<td>1.1</td>
</tr>
<tr>
<td>145</td>
<td>1.0</td>
</tr>
</tbody>
</table>

§ 4. Activation Data

Several activation cross sections have been measured as a complement to the gamma-ray work. The sample was irradiated for one to two half-lives in a known proton beam and then carried to the counting room where the resulting gamma rays (positron annihilation quanta in the cases of $^{11}$C and $^{18}$N and gamma rays in $^{10}$B in the case of $^{10}$C) were counted with a thallium-activated sodium iodide crystal for several half-lives.

The samples used were

- $^{12}$C: natural carbon;
- $^{14}$N: both liquid nitrogen and boron nitride (the latter for $^{13}$N activation only).

The yields of the individual activities were then found by separating the decay curve by a least squares method into exponentials of known half-lives, using the Ferranti MERCURY computer of the Computer Laboratory, Oxford. The results are shown in Table 5.

Table 5. Results of Activation Measurements

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$p + ^{18}$C</th>
<th>$p + ^{14}$N</th>
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<tr>
<td>Mean proton energy (MeV)</td>
<td>143</td>
<td>145</td>
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<tr>
<td>Activity</td>
<td>$^{10}$C</td>
<td>$^{13}$N</td>
</tr>
<tr>
<td>Yield (mbn)</td>
<td>$2.6 \pm 1.3$</td>
<td>$14 \pm 1$</td>
</tr>
</tbody>
</table>

The only results with which these can be compared are those of Symonds, Warren and Young (1957) who used protons of 420–980 MeV. To make a comparison we assume that cross sections for (p, pn) reactions fall off in the same way as in the $^{12}$C(p, pn) reaction: if this assumption is made the agreement between the $^{14}$N(p, pn) result presented here and those of Symonds, Warren and Young is good. Symonds et al. find an approximately constant cross section as the proton energy varies for the production of $^{10}$C from $^{12}$C + p. Our result suggests this constancy extends down to 140 MeV. Our cross section for the production of $^{11}$C from $^{14}$N + p is apparently about half of what it is at the higher energies.

Symonds, Warren and Young (1957) suggest that the lower cross section for the $^{14}$N(p, pn) reaction compared with that for the $^{12}$C(p, pn) reaction, as measured by activation methods, is because there is only one bound state in $^{13}$N while there are approximately eight in $^{12}$C. This explanation obviously does not hold at our energy as the gamma-ray data show that most of the production of $^{11}$C in the $^{12}$C(p, pn) reaction is direct production of the ground state, so that the cross section for production of the ground state of $^{11}$C is approximately 2.5 times that for the production of the ground state of $^{10}$N. This difference presumably reflects a difference in the structures of $^{12}$C and $^{14}$N.
§ 5. DISCUSSION OF KNOCKOUT REACTION RESULTS

On the usual direct interaction model of the reactions \( A(p, 2p) \) or \( (p, pn) A^-1 \) we are measuring the parentage of nucleus \( A \) (Lane and Wilkinson 1955); when we measure the relative populations of states of nucleus \( A^-1 \) produced in these reactions. In measurements of the energies of the outgoing protons in \( (p, 2p) \) reactions in the \( p \)-shell it has been found (Tyrén, Hillman and Maris 1958, Gooding and Pugh 1960) that the excitation spectra in nuclei \( A^-1 \) show pronounced peaks implying strong excitation of one or a few states in the residual nuclei. These peaks have been interpreted using a simple \( jj \)-coupling shell model, which interpretation would seem to conflict with the intermediate coupling picture which has been based on a wide range of work at lower energies (e.g. Inglis 1953, Kurath 1956, Lane 1953, 1955). In the work described here some details of the excitation spectra have been investigated in somewhat more detail and show lack of support for the \( jj \)-coupling interpretation; in the one case where calculations are available there is agreement with the intermediate coupling picture.

One has to be careful in applying the simple knockout model and not use it in cases where multiple collisions are important: for example, they are probably important in determining the polarization of neutrons produced in proton bombardment (Squires 1958 a). However the main effect of a second collision would be to evict further nucleons so our observation of bound states in nucleus \( A^-1 \) should select events where only a single collision has taken place; similarly the angular correlations of Gooding and Pugh (1960) should not be perturbed by multiple collisions as they restrict their attention to low excitation in \( ^{12}\text{B} \). The main causes of disturbance should be inelastic scattering of the incident nucleon before the knockout collision exciting nucleus \( A \) to an excited state and the inelastic scattering of either of the outgoing nucleons after the knockout collision excising nucleus \( A^-1 \) to a bound excited state. One can argue qualitatively that such processes would only contribute a very small amount to the \( (p, 2p) \) and \( (p, pn) \) reactions, as typical cross sections for inelastic scattering leaving nuclei in bound excited states are about 6 mbn to be compared with typical total reaction cross sections of about 250 mbn (we ignore elastic scattering as this does not change the ratio of states produced), so we can hope that they will not change our main conclusions. However detailed calculation of these effects would be valuable.

Now let us consider specific reactions, starting with \(^{12}\text{C}\) for which most detail is available, both experimental and theoretical. The cross section for producing \(^{11}\text{C}\) in its bound states is 44 mbn (Crandall et al. 1956) and of this the \(^{12}\text{C}(p,d)\) cross section is 4 mbn (Cooper and Wilson 1960) so the \(^{12}\text{C}(p, pn)\) cross section is 40 mbn; for both these reactions the ratio of population of states in \(^{11}\text{C}\) should be the same. For production of bound excited states we find: 1.99 MeV, 3 mbn; 4.8 MeV, 2 mbn; 6.5 MeV, 2 mbn, leaving 37 mbn for the ground state. This agrees with the \(^{12}\text{C}(p,d)\) measurements where only a group to the ground state is seen; weak groups of the relative strength seen here would not have been noticed in the \( (p, d) \) measurements. So we find for the ratio of population of first excited state \( (J = 1/2^-) \) to ground state \( (J = 3/2^-) \) in \(^{11}\text{C}\) a result \( 0.08 \pm 0.03 \). This agrees with neither the result for \( jj \)-coupling wave functions of zero nor the \( LS \)-coupling result of 0.5. Comparing with unpublished intermediate
coupling calculations by Kurath we find this result implies an intermediate coupling parameter of \(a/K = 6.4 \pm 1.0\) (see Fig. 9), which is consistent with the values \((a/K \approx 5.5)\) found in the lower energy work. Our result that most of the \(^{12}\text{C}(p, pn)\) reaction feeds the ground state of \(^{11}\text{C}\) agrees with the result that the ground state of \(^{11}\text{B}\) is the main state fed in the mirror \((p, 2p)\) reaction (Tyrén, Hillman and Maris 1958, Gooding and Pugh 1960).

Gooding and Pugh quote \(16 \pm 4\) mbn for the total cross section for the \(^{12}\text{C}(p, 2p)\) reaction leaving \(^{11}\text{B}\) in low states. This is in agreement with the \(^{12}\text{C}(n, 2n)^{11}\text{C}\) cross sections that have been measured as averages over neutron spectra peaked at various energies in this range (see for example results quoted by Rosenfeld, Swanson and Warshaw 1956). We have measured the \(^{11}\text{C}\) production in the \(^{12}\text{C}(n, 2n)\) reaction for a neutron spectrum with a peak at \(130\text{ MeV}\) and a maximum energy of \(155\text{ MeV}\). If one assumes the \((n, 2n)\) cross section to vary with energy in the same way as the \((p, pn)\) cross section the results correspond to a \(^{12}\text{C}(n, 2n)^{11}\text{C}\) cross section at \(143\text{ MeV}\) of \(17 \pm 3\) mbn. This agreement with the \((p, 2p)\) result of Gooding and Pugh confirms their assumption that there is no major contribution to the cross section from angular regions they have neglected. This gives a ratio of \(\sigma(p, 2p)/[\sigma(p, pn) + \sigma(p, d)] = 0.36 \pm 0.06\) in agreement with our result of \(0.29 \pm 0.13\) for the relative production of the first excited states of \(^{11}\text{B}\) and \(^{11}\text{C}\), thus lending support to the model discussed here. Finally we note that the ratio \(\sigma(p, 2p)/\sigma(p, pn) = 0.40 \pm 0.06\) to be compared with a ratio of \(0.56\) for the corresponding free-nucleon cross sections (Hess 1958).

![Fig. 9. Ratio of cross sections for producing first excited state and ground state in the \(^{12}\text{C}(p, pn)^{11}\text{C}\) reaction as a function of \((a/k)/(a/k + 5)\).](image)

One could argue that, as the relative feeding of the excited states is small, the main reaction is a simple feeding of the ground state, as predicted for \(J\)-coupling wave functions, with weak excitation of excited states due to inelastic scattering before and after the knockout collision. In this case, inelastic scattering before knockout would produce the four states of the \(p_{3/2}^3 s_{1/2}\) configuration, and on knocking out a \(p_{3/2}\) nucleon one gets ten states, so that each of them would be fed by a cross section of only a fraction of a millibarn (an estimate based on typical inelastic scattering cross sections). Inelastic scattering after knock-out should produce the same states as the \(^{11}\text{B}(p, p')\) reaction and we see from the measurements presented here that the first excited state is fed weakly, if at all, compared

\[\text{\dag We are indebted to Dr. Kurath for his permission to quote his unpublished results.}\]
to the second excited state, in this reaction. Thus it seems unlikely that it would be possible to explain the observed feeding in this way, starting from \( jj \)-coupling wave functions.

For the \(^{11}\text{B} \) ground state in \( jj \)-coupling there are four parent states. Writing them as \((J, T)\) the relative feeding of these states in \(^{10}\text{B} \) is: \((3, 0), 7/16; (1, 0), 3/16; (0, 1), 1/16; (2, 1), 5/16\). As the \( 0.72 \) and the \( 2.15 \) MeV states have \( J=1, T=0 \), while the \( 1.74 \) MeV state has \( J=0, T=1 \), we see that no \( jj \)-coupling assignment to these states will give agreement with cross sections found in this work. It would be interesting to be able to compare the experimental results with intermediate coupling calculations.

In the other \((p, 2p)\) and \((p, pn)\) reactions observed in this work there are no actual ratios of states to compare with predictions for \( jj \)-coupling wave functions. It is interesting however to compare the cross sections found with the total cross sections for the \( p \)-shell estimated from a simple model where the cross section for ejecting a \( p_{3/2} \) nucleon is taken to be the number of \( p_{3/2} \) neutrons or protons present, multiplied by the corresponding free-nucleon cross section (Hess 1958) and a nuclear absorption factor taken to be \( \exp(-kA^{1/3}) \). The value of \( k \) is found by taking 44 mb for the cross section for \(^{12}\text{C}(p,pn)\) and \(^{12}\text{C}(p,d)\) and 16 mb for the cross section for \(^{12}\text{C}(p,2p)\). (Such a model agrees quite well with the relative cross sections found by Tyrén, Hillman and Marn (1958) if we assume their results to be the same sample of the angular correlations in each case.) For such a model we find:

\[
\begin{align*}
7\text{Li}(p,pn)^6\text{Li} & \sigma_{\text{tot}} \sim 28 \text{ mbn}, \\
\text{ratio} & 3.56 \text{ MeV state/total, experiment, 0.05; prediction of model}, 0.21
\end{align*}
\]

\[
\begin{align*}
8\text{Be}(p,2p)^6\text{Li} & \sigma_{\text{tot}} \sim 9 \text{ mbn}, \\
\text{ratio} & 0.98 \text{ MeV state/total, experiment, 0.27; prediction of model}, 0.10; \text{assuming } J=3^+, 0.10; \text{assuming } J=1^+, 0.23
\end{align*}
\]

\[
14\text{N}(p,2p)^{13}\text{C} \sigma_{\text{tot}} \sim 15 \text{ mbn}.
\]

Three states with \( J=1/2^-, 3/2^-, 5/2^- \) should be formed with relative intensities \( 1:2:3 \). The \( J=3/2^- \) state should thus be formed with a cross section of 5 mbn. One would expect this state to be the 3/2 state at 3.68 MeV for which the cross section is found to be less than or equal to 1.5 mbn.

Thus in all of the three cases there are large discrepancies. Such a simple model cannot be accurate but one would be surprised if there were such large departures from it as would be needed to produce the ratios predicted for \( jj \)-coupling wave functions. Added to the direct evidence from the \(^{12}\text{C}(p,pn)\) and \(^{11}\text{B}(p,pn)\) reactions it does not seem that the simple \( jj \)-coupling interpretation is valid. One can speculate that the very localized excitation found in the residual nuclei in these reactions displays some particular property of the intermediate

\[\dagger\] These have been calculated by taking the ground state of \(^8\text{Li} \) to be the sole parent of the corresponding states in \(^6\text{Li} \) and using the relation between particles and holes given by Lane (1960), his formula (71). A further factor of \( 1/3 \) for the \( T=1 \) states comes from the coupling of the isotopic spins.

\[\ddagger\] In calculating the predicted ratios the fractional parentage coefficients of Edmonds and Flowers (1952) were used. In the case of \(^8\text{Be} \) the relation between particles and holes (Lane 1960) was also needed.
coupling wave functions. A similar simplicity is seen in the inelastic scattering reactions at these energies as is discussed in § 6 where it is suggested that inelastic scattering picks out certain states with particular properties in intermediate coupling. Perhaps similarly some particular states are picked out in the \((p, pn)\) and \((p, 2p)\) reactions.

The high yield of 4.43 MeV gamma rays from the bombardment of nitrogen is probably due to the \(^{14}\text{N}(p, pn)\) reaction producing an excited state or states of \(^{13}\text{N}\) which decay an appreciable part of the time by emitting a proton and leaving the first excited state of \(^{12}\text{C}\). From the \(^{14}\text{N}(p, 2p)\) measurements (Tyrén, Hillman and Maris 1958), it is known that states around 7.5 MeV in \(^{13}\text{C}\) are produced strongly in this reaction, so presumably mirror states are produced at the same energy in \(^{13}\text{N}\) in the \(^{14}\text{N}(p, pn)\) reaction. Such states in \(^{13}\text{N}\) can decay leaving \(^{12}\text{C}\) in either its ground state or first excited state (the states in \(^{13}\text{C}\) at this energy can decay only to the ground state of \(^{12}\text{C}\)). Thus it is not surprising that these states apparently decay about half the time to leave \(^{12}\text{C}\) in its first excited state, thus producing the 4.43 MeV gamma ray seen in this work. The alternative is that it is just one of the states that is formed when two nucleons are ejected by the incident proton from \(^{14}\text{N}\); it would however seem surprising that there would be such a large cross section for producing one particular state in \(^{12}\text{C}\). The difficulty in the former hypothesis is that one would expect negative parity states to be produced in \(^{13}\text{C}\) and \(^{13}\text{N}\) and there are no recorded states of negative parity at an excitation of about 7.5 MeV in these nuclei. However this is also a problem in understanding the results of Tyrén, Hillman and Maris, and we can only conclude that not all the states in this energy range in these nuclei are known. It would be interesting to search for these states; it would seem that the \(^{14}\text{N}(p, d)\), \(^{3}\text{He},\alpha\) or \((t, x)\) reactions would be suitable if sufficient energy were available.

One can make some remarks about other knockout reactions observed in this work. For reactions where two nucleons are ejected from the target nucleus, for example the production of \(^{10}\text{B}\) from \(^{12}\text{C}\), one would expect that one contributing process would be a \((p, 2p)\) or \((p, pn)\) process followed by one of the outgoing nucleons interacting with another nucleon and ejecting it. If this process was the only one responsible for the ejection of two nucleons one would expect that, as the ground states of \(^{11}\text{B}\) and \(^{11}\text{C}\) are produced approximately 0.81 of the time in the \(^{12}\text{C}(p, 2p)\) and \(^{12}\text{C}(p, pn)\) reactions, the relative feeding of states of \(^{10}\text{B}\) produced in the bombardment of \(^{12}\text{C}\) would be much the same as the relative feeding produced in bombardment of \(^{11}\text{B}\). From Table 2 one sees that this is definitely not so, implying that other processes must also contribute, for example the interaction of the incident proton with two-nucleon correlations in the nucleus.

§ 6. DISCUSSION OF INELASTIC SCATTERING REACTIONS

This work also provides some inelastic scattering cross sections which would be hard to measure otherwise. It is easy to show that the matrix elements determining radiative transition rates of electric multipole transitions are approximately the same as the direct interaction inelastic scattering matrix elements for these transitions. For radiative transitions the decay rate is given by

\[
T = \frac{8\pi (l + 1)}{l[(2l + 1)!]} \frac{1}{\hbar} \left(\frac{E}{\hbar c}\right)^{l+1} \left|\langle I_1 | M(l) | I_2 \rangle \right|^2 2I_1 + 1
\]

\[2\varphi^2\]
while the differential cross section for inelastic scattering for small momentum transfer in the plane-wave approximation is

\[
\frac{d\sigma}{d\Omega} = \frac{k_f}{k_i} \left( |M_0|^2 + \lambda |M_1|^2 \right) \left[ \frac{(q)^l}{(2l+1)!!} \right]^2 (2l+1)^{-1} \frac{\langle I_f | M(l) | I_i \rangle^2}{2I_i + 1}
\]

where \( \langle I_i | M(l) | I_f \rangle \) is the reduced matrix element for the transition from state of spin \( I_i \) to state of spin \( I_f \) corresponding to the interaction operator

\[
M(l, \mu) = \sum_{k} r_{k} Y_{l\mu}(\theta_k, \phi_k),
\]

the summation being over protons for the radiative decay and over all nucleons for the inelastic scattering (one presumes this difference is unimportant in the 1p-shell). \( M_0, M_1 \) are the matrix elements of the nucleon-nucleon interaction corresponding to no-spin-flip and spin-flip respectively and \( \lambda \) is the ratio of the nuclear spin-flip and no-spin-flip matrix elements (Kerman, McManus and Thaler 1959). \( q = k_i - k_f \) is the momentum transfer in the inelastic scattering.

One can attempt to relate these matrix elements quantitatively, as has been done by Squires (1958 b) who showed that the matrix element for exciting the 4-43 MeV state of \( ^{12}\text{C} \) in the \( ^{12}\text{C}(p, p') \) reaction is the same as the radiative matrix element determined by Coulomb excitation (Morpurgo 1956) but to do this the amount of calculation is considerable. Here we attempt a simpler analysis taking ratios of inelastic scattering cross sections to equal the corresponding ratios of radiative decay rates. We can expect this might work if we choose pairs of transitions of the same multipolarity, where the angular distributions are closely similar, and in the same shell, where the change in cross section is going from the plane-wave approximation to the true distorted-wave theory should be much the same. We follow Wilkinson (1956) in quoting \( |M|^2 \), the ratio of the experimental decay rate to Weisskopf’s extreme single particle result. Thus from the known mean life of the 4-43 MeV state of \( ^{12}\text{C} \), corresponding to \( |M|^2 = 1.74 \) (all the gamma-ray data used here are taken from Ajzenberg-Selove and Lauritsen (1959) except where other references are given), and the inelastic scattering cross sections for exciting the 4-43 MeV state of \( ^{12}\text{C} \) and the 4-46 MeV state of \( ^{11}\text{B} \), we find for the electric quadrupole decay of the \( ^{11}\text{B} \) state: \( |M|^2 = 4.3 \). To compare with this we find the rate of electric quadrupole decay of this state from the known rate of decay, which is largely magnetic dipole, and the E2/M1 ratio of the order of 0.05 determined from angular distributions in the \( ^{7}\text{Li}(x, \gamma) \) reaction (Jones, Johnson and Wilkinson 1959), finding for the electric quadrupole radiative decay of the 4-46 MeV state of \( ^{11}\text{B} \): \( |M|^2 = 6.7 \). This agreement is remarkable, particularly when one considers the uncertainty in extracting E2/M1 ratios from angular distributions. A similar comparison of the measured lifetimes of the 4-43 MeV state of \( ^{12}\text{C} \) and the \( J = 2^+ \) state of \( ^{16}\text{O} \) at 6.92 MeV predicts an inelastic scattering cross section of 2.8 ± 0.85 mbn for the latter to be compared with the observed 1-5 mbn (Clegg et al. 1960, unpublished). Thus one sees that with this naive method one can apparently, from inelastic scattering cross sections, determine electric multipole radiative widths of states within an accuracy of a factor or two. A more refined analysis would be desirable taking into account

\( ^\dagger \) A similar relation between inelastic scattering cross sections and radiative transition rates has been noted in the inelastic scattering of 23 MeV protons from medium-weight nuclei (Cohen and Rubin 1958).
the absorption of protons in the inelastic scattering, which must cause the inner parts of the nucleus to be weighted less in the inelastic scattering matrix elements than they are in the radiative matrix elements.

We apply this procedure to the electric quadrupole transition from the 2.15 MeV state of $^{10}$B to the ground state comparing its excitation with the 4.43 MeV state of $^{12}$C, for which both the inelastic scattering cross section and the radiative lifetime are best determined, finding an estimate for the radiative decay of this state of $|M|^2 = 11$ corresponding to a radiative width of $9.7 \times 10^{-4}$ eV. From the known branching ratios of transitions from this state one then finds radiative widths for the magnetic dipole transitions to the 0.72 and 1.74 MeV states, giving $|M|^2 = 0.66$ for the transition to the 1.74 MeV state and $|M|^2 = 0.02$ for the transition to the 0.72 MeV state, which are very respectable results for magnetic dipole transitions in the 1p-shell (Wilkinson 1956). From the known mean life of the radiative transition from the 0.72 MeV state of $^{10}$B we estimate a cross section of 0.3 mb for the excitation of this state in inelastic scattering which does not disagree with our measurements.

The excitation of the 3.95 MeV state of $^{14}$N is due to both the monopole and quadrupole matrix elements. The latter presumably contributes most strongly to the total inelastic scattering cross section, as the former will only contribute to the angular distribution at forward angles. Making this assumption the electric quadrupole radiative width of this state corresponds to $|M|^2 = 0.57$.

One sees that inelastic scattering apparently provides a method for picking out these states which make strong electric multipole radiative transitions to the ground state and one can ask what are the particular properties of the states so selected. It is found that these results fit well with a distorted nucleus model of the 1p-shell where states in the rotational band based on the ground state are strongly excited in inelastic scattering while rotational bands based on excited states are not. This model, which is presumably an approximation to the procedures of Kurath and Piemäns (1959) and thus an aspect of the intermediate coupling shell model, is described fully elsewhere (Clegg 1961).

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† These results can be compared with $|M|^2 = 1.7$ for the former and $|M|^2 = 0.005$ for the latter calculated for intermediate coupling wave functions by Kurath (1957).