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SOME (t,p) REACTIONS IN LIGHT NUCLEI

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ABSTRACT.

The (t,p) reactions induced in the target nuclei ^{10}B, ^{11}B, ^{12}C, ^{16}O and ^{27}Al have been investigated at an incident triton energy of 5.5 MeV. The angular distributions of the observed proton groups have been compared with a theory of double stripping and good agreement has been obtained with the theoretical predictions for transfers of 0, 1, 2 and (more tentatively) 3 units of orbital angular momentum.

A new level in ^{12}B at an excitation of 4.297 MeV is reported. Spin and parity assignments have been made for the levels of ^{14}C at excitations of 6.582 MeV (1-), 6.725 MeV (probably 3-), a hitherto unreported level at 7.009 MeV (C+)

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* This work was performed when one of the authors (F. de S. Barros) was at the University of Manchester.

and at 7.335 MeV (probably 2-). The existence of levels in ^{18}O at 3.634 and 4.448 MeV has been confirmed and the spins and particles have been determined to be 0^+ and 3- respectively. The spin and parity of the state in ^{18}O at 3.915 MeV excitation has also been determined as 2+.

The behaviour of the $^{16}O(t,p)^{18}O$ reaction leading to the ground and first four excited states of ^{18}O has been found to be consistent with the ^{18}O configurations predicted by the intermediate coupling theory.

The atomic mass excess of ^{29}Al has been found to be -9.647 ± 0.015 MeV and the excitations of forty two new levels of ^{29}Al have been measured.

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1. INTRODUCTION.

Published information about ^{3}He induced reactions is now steadily accumulating (e.g. Hinds and Middleton 1959 a, 1959 b; Forsyth et al 1960, Taylor et al 1960) and previous work on these reactions have recently been reviewed by Bromley and Almqvist (1960). Relatively little information has previously been available about nuclear reactions induced by tritium except in the lightest nuclei and at very low bombarding energies (c. f. Ajzenberg Selove and Lauritsen 1959).

The mechanism of tritium induced reactions is of considerable interest and, as will be seen, they can also become a useful tool in nuclear spectroscopy. Many nuclear states may be reached by them that have not previously been observed or studied in detail because of the absence of suitable alternative reactions; the (t,p) process described here may be particularly valuable in this respect since it is governed by exceptionally stringent selection rules. In the course of these experiments the (t,d) and (t,α) reactions on several of the target nuclei have also been investigated, and the results will be treated separately in subsequent papers.

2. EXPERIMENTAL TECHNIQUES.

Tritium ions were accelerated in the Manchester University Van der Graaff generator. Initially, 4 c. c of tritium (supplied by A.E.R.E. Harwell) was mixed with 200 c.c. of helium and beam s of up to 0.4 μ amp of tritons were obtained on the target spot. This mixture provided about 25 hours running time. The gas pumped from the accelerator was collected and purified by absorption in activated uranium turnings at 150°C (Allen and Almqvist 1953). The remaining gas in contact with the uranium was presumed to be fairly pure helium but it possibly contained some tritium. A further 200 c.c. of helium and 4 c.c. of tritium were then added to this residual gas together with the tritium recovered by heating the uranium to 400°C. This second mixture provided a tritium beam for more than 70 hours and was still not completely exhausted. Unfortunately, the beam current at the target could not then be increased above 0.1 μ amp and was usually much less. Contamination of the beam with ^{3}He ions was estimated as less than 0.05%, though up to about 0.5% of singly ionised HD molecules was present especially in the second run.

The targets were evaporated on to backings of thin carbon foil. The thickness of the backings and targets were measured by an alpha-particle gauge and the quoted errors in the cross-sections appear to be justified by the consistency of the results obtained from the same reactions in several targets of different thicknesses (for example, $^{12}C(t,p_o)^{14}C$). The targets consisted of natural boron, carbon, silicon dioxide and aluminium respectively. The reaction products were analysed with a broad range magnetic spectrograph which has been described previously (Barros et al 1959). In the case of the boron and carbon targets two different settings of the spectrograph field were required to cover the desired range of energies of the outgoing particles. The spectrograph was recalibrated with α-particles from ^{210}Po and ThC' immediately before these experiments.

3. RESULTS.

The peak differential cross-sections for the observed (t,p) reactions leading to discrete final states were found to be, on average, lower than those of either the (t,d) or (t,α) reactions produced in the same targets.

$^{10}B\ (t,p)\ ^{12}B$

The ground state Q-value for the $^{10}B(t,p)^{12}B$ reaction was found to be 6.346 ± 0.006 MeV. States of ^{12}B were found at excitations of 1) 0.955; 2) 1.673; 3) 2.627; 4) 2.73; 5) 3.393; 6) 3.754; 7) 4.297; 8) 4.514; 9) 5.[illegible] 10) 5.612; 11) 5.724 MeV. With the exception of the fourth and ninth excited states the accuracy of the measured excitations is ± 0.008 MeV. The level at 4.297 MeV has not been previously reported.

The fourth excited state group was observed only at the larger angles with an extremely low cross-section of about 40 microbarns/sterad. The ninth excited state group was observed at 40° only; the measured excitation agrees with that previously reported but it is of low intensity and particularly difficult to observe because of its width, which was found to be very approximately Γ = 40 kev.

The width of several other groups could be measured directly provided they were greater than 20 kev. Thus, the widths of the levels at 3.754, 4.514 and 5.61 MeV were found to be Γ = 45, 50, and 145 kev respectively. The measured width of the level at 4.514 MeV which is identified with that previously reported at 4.54 $\pm$ 0.02 MeV is much smaller than that derived from observation of the resonances of the $^{11}B(n,n)^{11}B$ reaction (Bockelman et al 1951).

Our result is obtained from the spectra at two angles where the proton group leading to this level was clear of the intense proton group from the $^{16}O(t,p)^{18}O$ reaction (which overlapped with it at some angles as it does, for example, in the 20° spectrum shown in figure 1). The effect of overlap with a large group would, of course, tend to <u>increase</u> the observed width.

A proton continuum, attributed to the $^{10}B(t,pn)^{11}B$ reaction was present and it increases in intensity with decreasing proton energy down to the lower limit of observation. ^{12}B is unstable against neutron emission at excitations above 3.36 MeV. The continuum does not very rapidly in intensity with the angle of observation. The peak differential cross-section of the $^{11}B(t,p_o)^{13}B$ reaction which has been described in a previous publication (Muto et al 1960) is very much larger than that of any of those from the $^{10}B(t,p)^{11}B$ reaction.

Angular distributions for the p_o, p_1, p_6 and p_{10} groups of the ^{10}B(t,p) reaction are shown in figure 2. The p_4, p_9 and p_{11} groups were too weak to yield reliable angular distributions and the p_2 group overlaps with the strong ^{12}C(t,p_o) group at angles below 40°. The maximum observed differential cross section for the p_2 group was 0.70 millibarns/sterad (at 40°). The p_8 group overlaps at lower angles with that from ^{16}O(t,p_1)^{18}O but its cross-section is approximately constant in the range of from 30° to 70° in the centre of mass system at about 0.25 millibarns/sterad. The p_3 and p_5 groups are essentially isotropic in the range from 20° to 70° and they have differential cross-sections of 0.20 and 0.45 millibarns/sterad respectively the p_7 group does not show a stripping pattern and reaches a maximum differential cross-section of only 0.17 millibarn/stead.

^{12}C (t,p)

A proton spectrum from the ^{12}C(t,p) reaction at an angle of observation of 30° and at the lower field setting is shown in figure 3. The ground state proton group was observed in a series of exposures at higher magnetic fields. At the lower field settings a further six proton groups corresponding to excited states in ^{14}C at 1) 6.[illegible]0 2) 6.582, 3) 6.725, 4) 6.893, 5) 7.009 and 6) 7.336 MeV to within ± 0.[illegible]0 MeV. The level at 7.009 MeV has not, apparently, been reported previously but the remainder are in good agreement with the accepted values.

The differential cross sections of the proton groups leading to the seven states of ^{14}C have been measured at a number of angles and the angular distributions are shown in figure 2, with the exception of the weak and relatively isotropic p_4 and p_6 groups (which have peak differential cross-sections of only 0.4 and 0.3 millibarns/sterad respectively.

$^{16}O(t,p)$

A proton spectrum obtained from the silicon dioxide target is shown in figure 4. No attempt has yet been made to analyse all the proton groups leading to levels of ^{30}Si which correspond to excitations in the approximate range of 7 MeV to 12 MeV. Levels in ^{18}O were observed corresponding to the ground state and to excitations of 1) 1.979, 2) 3.552, 3) 3.634, 4) 3.915, and 5) 4.448 MeV (± 0.005 MeV). The levels at 3.634 and 4.448 MeV are relatively new but correspond to those which have previously been observed by Jarmie (indirect private communication).

$^{27}Al(t,p)$

The $^{27}Al(t,p)^{29}Al$ reaction was observed at nine angles in the range from 10° to 90° in the laboratory system. The proton spectra have been scanned across the whole width of the exposed plate at five angles (15°, 30°, 50°, 60° and 90°) but only partially at the remaining four angles. The 50° spectrum is shown in figure 5. Proton groups corresponding to transitions to the ground state and forty two excited states of ^{29}Al were identified by the variation of energy of the protons with angle. The chance that any of the weak proton groups in the spectrum, although showing the correct angular energy variation might be due to the $^{27}Al(^3He,p)^{29}Si$ resulting from ^3He contamination of the beam, seems negligible. This conclusion is based on intensity considerations (using values of the $^{27}Al(^3He,p)^{29}Si$ cross-sections which we had observed in previous experiments) and on a search for any groups at positions calculated for known levels in ^{29}Si. It thus appears certain, for example, that the weak p_1 group does not arise in this way. The energy resolution is 15-20 kev depending slightly on the position along the plate. The measured excitations of the levels of ^{29}Al are given in table 1. These excitations were derived, in most cases, from observations at five angles, except in the region of the strong proton group from the $^{12}C(t,p_0)$ reaction which interfered with part of the spectrum (usually obscuring only one group from ^{29}Al). The relative position of this $^{12}C(t,p_0)$ group varies rapidly with angle. Some weaker groups at the lower energy and of the spectrum were also observed at fewer than five angles, as indicated in the table.

The beam energy was accurately determined at four angles of observation from the reaction $^{12}C(t,p_0)^{14}C$, and from the relatively intense $^{27}Al(t,d_0)^{28}Al$ reaction. It was also derived from the energies of elastically scattered deuterons present in the beam as HD molecules. Good agreement was obtained, between the values of the beam energy derived in the above ways using the accepted Q-values for the reactions.

The ground state Q-value for the $^{27}Al(t,p)$ reaction was then found to be 8.678 ± 0.006 MeV, a value which differs by about 300 kev from that obtained using the accepted mass excess for $^{29}Al(-9.35 \pm 0.1$ MeV, Endt and Braams 1957). An accurate value of the atomic mass excesses of ^{29}Al may be found from our results using the known mass excesses for $^{27}Al(-9.219 \pm 0.010$ MeV) and for the triton and proton (15.835 and 7.585 MeV respectively) Thus, the atomic mass excess of ^{29}Al was found to be -9.647 ± 0.015 MeV.

The angular distributions of two of the many proton groups from this reaction are shown in figure 6. The angular distributions of the remaining groups require further analysis; but they appear in general to vary in intensity less rapidly with angle than the two shown.

4. DISCUSSION OF RESULTS.

a) Theory.

Recently Newns (1960) has developed a theory of double stripping using a method similar to that used by Bhatia et al (1952) in the treatment of deuteron stripping. This theory may be applied to both (^{3}He,p) and (t,p) reactions and the form of the angular distribution is essentially given by $\sum_L \alpha_L \, j_L^2 (kr)$, where L is the total angular momentum transferred in the process. The selection rules which determine L are $\underline{J}_f = \underline{J}_i + \underline{L} + \underline{S}$; where S is the combined spin of the two captured nucleons L must take even values if the initial and final states have the same parity and odd values if they have different parily. $\underline{L} = \underline{\ell}_1 + \underline{\ell}_2$ where ℓ_1 and ℓ_2 are the orbital angular momenta of the two captured nucleons. For (^{3}He,p) reactions S may be 0 or 1 but in the case of (t,p) reactions S is restricted to 0 only. Thus, for the (t,p) reaction the selection rules are exceptionally restrictive compared with either (d,p) or (^{3}He,p) reactions. If the spin of either the initial or final states is zero, then at the most one value of L is possible and, if found, it uniquely determines the spin of the other state. A zero value of L indicates that the initial and final states have the same spins and parities. In contrast with the (d,p) or (^{3}He,p) reactions, some (t,p) stripping transitions would be completely forbidden, for example, between states one of which had zero spin and positive parity and the other even spin and negative parity. In transitions in which more than one L value is allowed to the relative values of the coefficients α_L would depend on the configurations of the states involved.

b) Transition to ground states.

Particularly simple angular distributions with relatively large peak differential cross-sections have been observed in the ground state transitions of $^{12}C(t,p)^{14}C$, $^{16}O(t,p)^{18}O$, $^{27}Al(t,p)^{29}Al$ figures 2 and 6) and in the case of the previously published result for $^{11}B(t,p)^{13}B$ (Muto et al 1960). In all the above transitions a strong L = 0 transfer is indicated: this is the only value of L allowed by the selection rules for the transitions $^{12}C \rightarrow {}^{14}C$ and $^{16}O \rightarrow {}^{18}O$ using the known initial and final spins and parities (0 + in both cases). The ground states of ^{27}Al and ^{29}Al have spin and parity 5/2 + (Endt and Braams 1957) and the results may be regarded as confirmation of this assignment for ^{29}Al. However, additional L values of 2 and 4 would be allowed by the selection rules in this case. The $^{11}B(t,p)^{13}B$ transition ($3/2^- \rightarrow 3/2^-$) also has an additional allowed L-value of 2.

The distinctive angular distributions and relatively large cross-sections which have been observed in these four ground state transitions suggests that the final nuclei (^{13}B, ^{14}C, ^{18}O and ^{29}Al) have configurations consisting of a core composed of the target nucleus which is essentially undisturbed by the addition of the two neutrons stripped off the triton. The predominance of the L = 0 transition which is observed in these transitions indicates that the orbital angular momenta of the two neutrons added to form the final nucleus (ℓ_1, ℓ_2) must be equal (and anti-parallel, if they are greater than zero).

The $^{16}O(t,p)^{18}O$ angular distribution has been referred to in a previous publication (Jaffe et al 1960); where, by comparing it with the known angular distributions of the protons from the $^{16}O(^3He,p)^{18}$ reaction, the 1.044 MeV excited state of F^{18} has been identified as the first T = 1 state of that nucleus. In the (t,p) angular distribution the observed differential cross-section falls to a strikingly low first minimum which is only 1/200 times as large as at its peak. This indicates that direct reaction mechanisms are probably the only type which contribute significantly to the cross-section. The second maximum is larger than that predicted by the square of the Bessel function $j_0^2(kr)$ and the discrepancy with the fit of this second maximum with theory would be even greater if the theoretical curve was multiplied by the form factor proposed by Newns. The size of the second maximum may be caused by partial absorption of the outgoing protons by interactions neglected in the Newns theory of double stripping; such effects have recently been reviewed in terms of a semi-classical model by Austern (1960).

In contrast to the ground state transitions discussed above, the $^{10}B(t,p)^{12}B$ angular distribution could not be fitted with the theory and the peak differential cross-section is small; it is doubtful if double stripping contributes significantly to this reaction. This result may be a consequence of the relative configurations of the ^{10}B and ^{12}B ground states or alternatively to deficiencies in the theory. Macfarlane and French (1959), however, have been able to interpret the results of some (d,p) stripping data reasonably well in terms of jj coupling configurations of $(p_{3/2})^6$ and $(p_{3/2})^7\ p_{1/2}$ for ^{10}B and ^{12}B respectively, and on this assumption (t,p) stripping might be expected with $\ell_1 = \ell_2 = 1$; $L = 2$. This mechanism is not observed. Similar difficulties are also found for the $^{10}B(t,p)$ reaction leading to most of the excited states of ^{12}B(see below).

c) Transitions to Excited States.

$^{10}B(t,p)^{12}B$

The $^{10}B(t,p)$ reaction is especially difficult to interpret because of the relatively complicated configuration of the target nucleus and the fact that the spins and parities of the first five excited states have not previously been determined by alternative methods. The measured differential cross-sections leading to all the observed excited states except that at 5.612 MeV (p_{10}) are small and the angular distributions are not characteristic of double stripping. The p_{10} group, however, is strong and has an angular distribution which can be fitted with a curve for $L = 1$, indicating that the level has negative parity (figure 2). The configuration of this level is perhaps relatively simply related to the ^{10}B ground state and may correspond to a ^{10}B core with two additional neutrons, one added to the p shell and the other entering either a 2s or 1d state.

^{12}C(t,p)^{14}C

The first and second excited state groups of the ^{12}C(t,p) reaction have angular distributions which can both be fitted with theoretical curves having L = 1 (figure 2). This value of L is the only one allowed for the transition to the first excited state which has the known spin and parity 1-. The spin and parity of the second excited state of ^{14}C is determined unambiguously as 1- from the observed angular distribution. The fifth excited state at 7.009 MeV, which has not previously been reported, can be fitted with a theoretical curve having L = 0. Because of the low Q-value (-2.375 MeV), the maximum of the experimental curve corresponds to the relatively low second maximum of the spherical Bessel function of zero order. Hence, this transition must be considered to be a relatively strong one. The selection rules determine a spin and parity of 0 + for this new level. This state could be identified with the state having the configuration $(p_{3/2})^2$ having spin parity and isobaric spin 0 +; 1 discussed by Inglis (1953) which should appear at approximately this excitation. It seems unlikely, however, that such a configuration would be strongly formed by ^{12}C(t,p)^{14}C double stripping since, assuming strong jj coupling for ^{12}C, considerable rearrangement of the initial ^{12}C nucleus would be required. The observed result therefore suggests that the 7.009 MeV level is predominately a p^8d^2 configuration (which could also be present in this region of excitation).

Formation of the state by strong (t,p) stripping on ^{12}C would then be expected, in agreement with the observations.

The $^{12}C(t,p_4)$ differential cross-section is very small; if the spin and tentative parity assigment of 0- is correct, (t,p) stripping is forbidden. The $^{12}C(t,p_6)$ group is also weak and almost isotropic; a spin of either 2 or 3 has been assigned to this level and it is known to have negative parity from the $^{13}C(d,p)^{14}C$ stripping reaction. A spin and parity of 2- for this state would forbid stripping and explain the observed result.

The p_3 group has been very tentatively fitted with a theoretical curve having $L = 3$, though a somewhat large radius has been used. The differential cross section is relatively large and stripping appears to be allowed. The spin and parity of the third excited state has previously been assumed to be either 2- or 3-; since (t,p) stripping on ^{12}C to this level would be forbidden if its spin and parity were 2-, the large observed cross section and the shape of the angular distribution appears to indicate that 3- is the most likely alternative. Improved angular distribution data over an extended range of angles is required, however, to confirm this result. The information obtained about the levels of ^{14}C and ^{18}O (see below) is summarised, together with the previously available data, in figure 7.

$^{16}O(t,p)^{18}O$

The angular distributions of the p_1 and p_4 groups agree quite well with j_2^2 (kr) using r = 7.5 f and 7.0 f respectively. The previously unknown spin and parity of the fourth excited state is therefore determined unambiguously by the selection rules as 2+. An identical result is also obtained for the first excited state, already known to be 2+. The peak differential cross-sections for the transitions to the two states are roughly similar. The first excited state is expected to have configuration which is predominantly singlet (${}^{1}D^{(dd)} + {}^{1}D^{(ds)}$) with an admixture of the triplet configurations ${}^{3}P^{(dd)}$, ${}^{3}F^{(dd)}$ and ${}^{3}D^{(ds)}$ as is also the fourth excited state* (t,p) stripping should proceed to both these excited states to an extent depending on the proportion of the singlet states present in the configuration. Hence the fairly good L = 2 transfers and the roughly similar cross-sections which are observed are in good agreement with the above assignments.

The spin and parity of the third excited state at 3.634 MeV is also determined by the observed angular distribution and is found to be 0+. The peak differential cross-section for the (t,p) reaction leading to this state is only one fourteenth as large as that to the 0+ ground state. The ground state configuration is very predominantly ${}^{1}S^{(dd)}$ whereas that of the 3.634 MeV state is chiefly ${}^{1}S^{(ss)}$. For the (t,p) stripping reaction the transition to the ground state which should proceed with $\ell_1 = \ell_2 = 2$ should be enhanced relative to that of the third excited state ($\ell_1=\ell_2=0$) by a factor of five from purely statistical factors contained in the stripping theory. There is also a difference in the Q-values for these two transitions and in fact the products of the squares of the spherical Bessel functions ($j_0^2(kr)$ with the appropriate arguments) and the statistical factors are found to be quite closely proportional to the observed cross-sections.

The known spin and parity of 4+ of the second excited state of ${}^{18}O$ unambiguously predicts an $L = 4$ angular momentum transfer for formation of this state by double stripping of the triton. The differential cross-section of up to 1.2 millibarn/sterad which is observed is somewhat larger than that of the weakest transitions discussed here, but there is no agreement between the angular distribution and the theoretical predictions. The double stripping theory of Newns, in its complete form contains a series of terms in the expression for the angular distribution ($n \geqslant 1$). These terms are neglected when the single Bessel function term is used. The terms of this series were computed, taking $\ell_1 = \ell_2 = 2$, $L = 4$, corresponding to the capture of two neutrons into d states to form the 4+ level of ${}^{18}O$. The summation of the series up to $n = 3$ was computed and it was found that the effect on the shape of the theoretical curve is negligible, so that the disagreement between the observed distribution and the theory cannot be accounted for by the neglect of such terms. However, the configuration of this 4+ state is predominantly triplet (${}^{3}F(dd)$) though quite a large admixture of the singlet ${}^{1}G(dd)$ should be present. In view of the fact that (t,p) stripping to the triplet configuration is forbidden and transitions involving large values of L should, in any case, be relatively weak, the absence of clear evidence of a stripping process is perhaps not surprising.

The final group from the ${}^{16}O(t,p){}^{18}O$ reaction is that leading to the fifth excited state at 4.448 MeV. The protons from this group were sufficiently energetic to fall within the observed spectra only at the smaller angles, though the relative cross-sections at 40°, 50° and 60° could be obtained approximately from the boron exposures where ^{16}O was present as an impurity. The observations indicate an L = 3 transfer to this state and the spin and parity 3- may be tentatively assigned to the level.

$^{27}Al(t,p)^{29}Al$

Insufficient information is available about the levels of ^{29}Si at energies high enough to compare any levels of isobaric spin T = 3/2 with the observed levels of ^{29}Al. The ground state spin and parity of ^{27}Al is 5/2+. The observed L = 0 stripping transfer to the ground state of ^{29}Al indicates that it may be formed by the simple addition of two neutrons with antiparallel spins and most probably these both enter the 2s shell. The angular distribution of the p_8 group also indicates some simple relationship between the configuration of this level and that of the ground state of ^{27}Al and that this level has positive parity. A more complicated relationship is expected between the remaining levels observed in ^{29}Al and the ^{27}Al ground state.

5. CONCLUSIONS.

For all the observed (t,p) reactions in which reasonable large peak differential cross-sections occur (i.e. $\gtrsim$1.5 millibarn/steard)in the angular distribution an agreement with the theory of double stripping has been obtained. Good agreement with theory is apparent in several cases involving orbital angular momentum transfers L = 0, 1, 2 and (more tentatively) L = 3. In all cases where the spins and parities of both the initial and final states was known from other data the expected value of L was obtained in the (t,p) reaction. The validity of the theoretical selection rules for (t,p) stripping have been established and the results suggest that where (t,p) stripping is forbidden, only relatively small differential cross-sections (of less than ~ 0.5 millibarns/sterad) may be expected. Verification of the selection rules confirms that the two neutrons can only be stripped from the triton with anti-parallel spins. The probability of (t,p) stripping may also be reduced because of unfavourable configurations of states of the initial or final nucleus (as for the $^{10}B(t,p)$ reaction). In such cases, failure of the angular distribution of the outgoing protons to conform with the predictions of the theory is observed, but such transitions have only small cross-sections (~ 0.5 millibarns/sterad).

Comparison of the observations with the theory can usually best be made using it in its simplest form (Newns 1960). There is evidence that inclusion of the proposed form factor would tend to reduce excessively the predicted relative cross-section at the larger angles; also, our calculations have shown that higher terms would not significantly affect the predicted shape of the angular distribution (though the affect on the absolute cross-section may not be negligible).

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Footnote:

* The quoted configurations for the levels of ^{18}O are based on the intermediate coupling calculations of Elliot and Flowers (1955) which have recently been recomputed by D. Wilmore using a revised exchange mixture. The new spins and parities determined in this investigation are entirely consistent with the predictions of the theory.

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TABLE 1

EXCITATIONS OF LEVELS OF ^{29}Al

Level No.	Excitations (MeV)	Level No	Excitation (MeV)
1	1.406	28	5.732
2	1.762	29	5.869
- 3	2.334	30	5.916
4	2.875	31	6.002
5	3.071	32	6.063
6	3.191	33	6.152 (4)
7	3.434	34	6.358
8	3.584	35	6.412 (4)
9	3.646 (4)	36	6.449 (3)
10	3.676 (4)	37	6.469 (3)
11	3.941	38	6.517
12	3.993	39	6.588
13	4.064 (4)	40	6.674
14	4.228 (4)	41	6.758
15	4.411 (4)	42	6.840 (4)
16	4,646 (3)[a]		
17	4.716 (4)		
18	4.846		
19	4.939[a]		
20	5.024		
21	5.154		
22	5.190		
23	5.267		
24	5.395 (3)		
25	5.424		
26	5.561[a]		
27	5.654		

Most of the levels were observed at five different angles, if not, the numbers in parenthesis indicate the number of angles at which they were identified.

[a] Levels suspected of having multiplet structure.

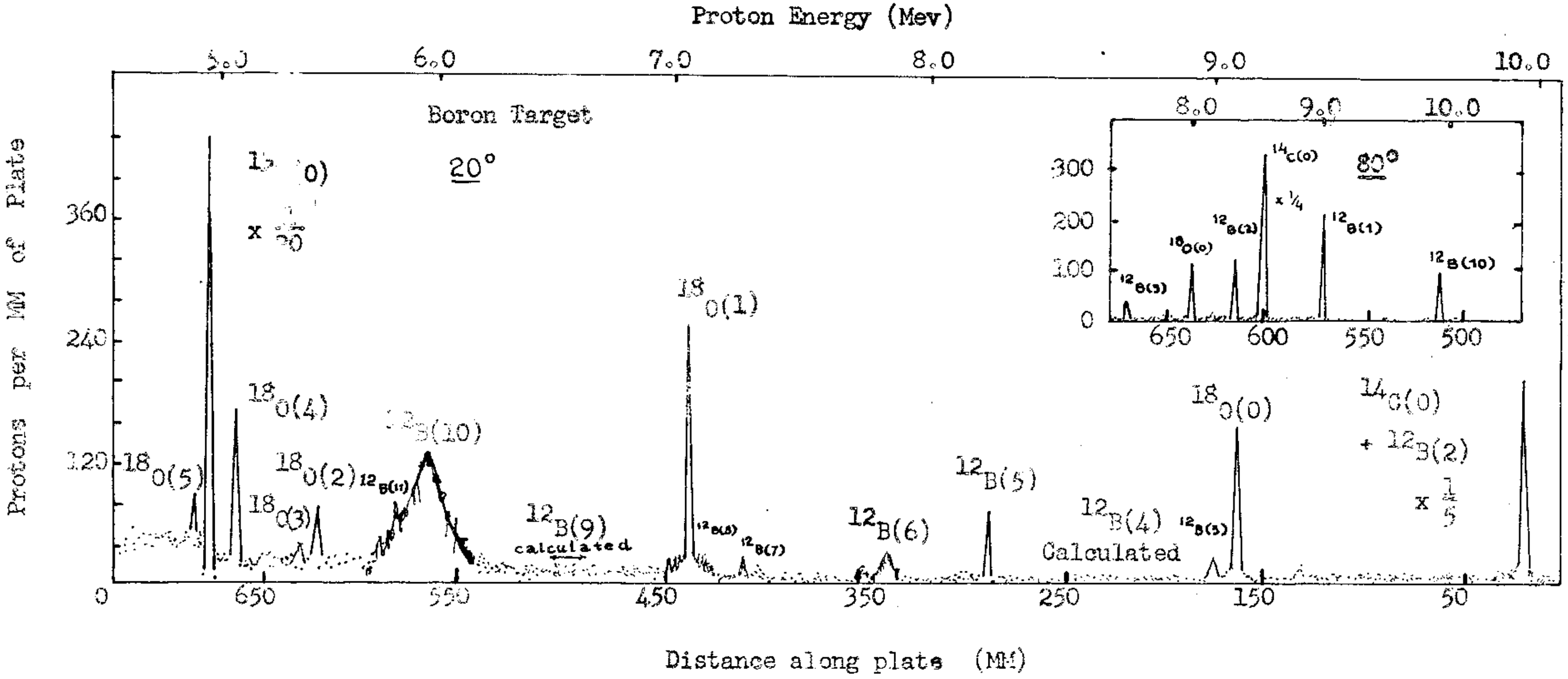
Proton Energy (Mev)
5.0
6.0
7.0
8.0
9.0
10.0
Boron Target
20°
x 1/50
18O(5)
18O(4)
18O(3)
18O(2)
12B(11)
12B(10)
12B(9)
calculated
18O(1)
12B(8)
12B(7)
12B(6)
12B(5)
12B(4)
Calculated
12B(3)
18O(0)
14C(0)
+ 12B(2)
x 1/5
80°
14C(0)
x 1/4
12B(2)
12B(1)
12B(10)
12B(3)
300
200
100
0
650
600
550
500
Protons per MM of Plate
360
240
120
0
650
550
450
350
250
150
50
Distance along plate (MM)

Fig. 1

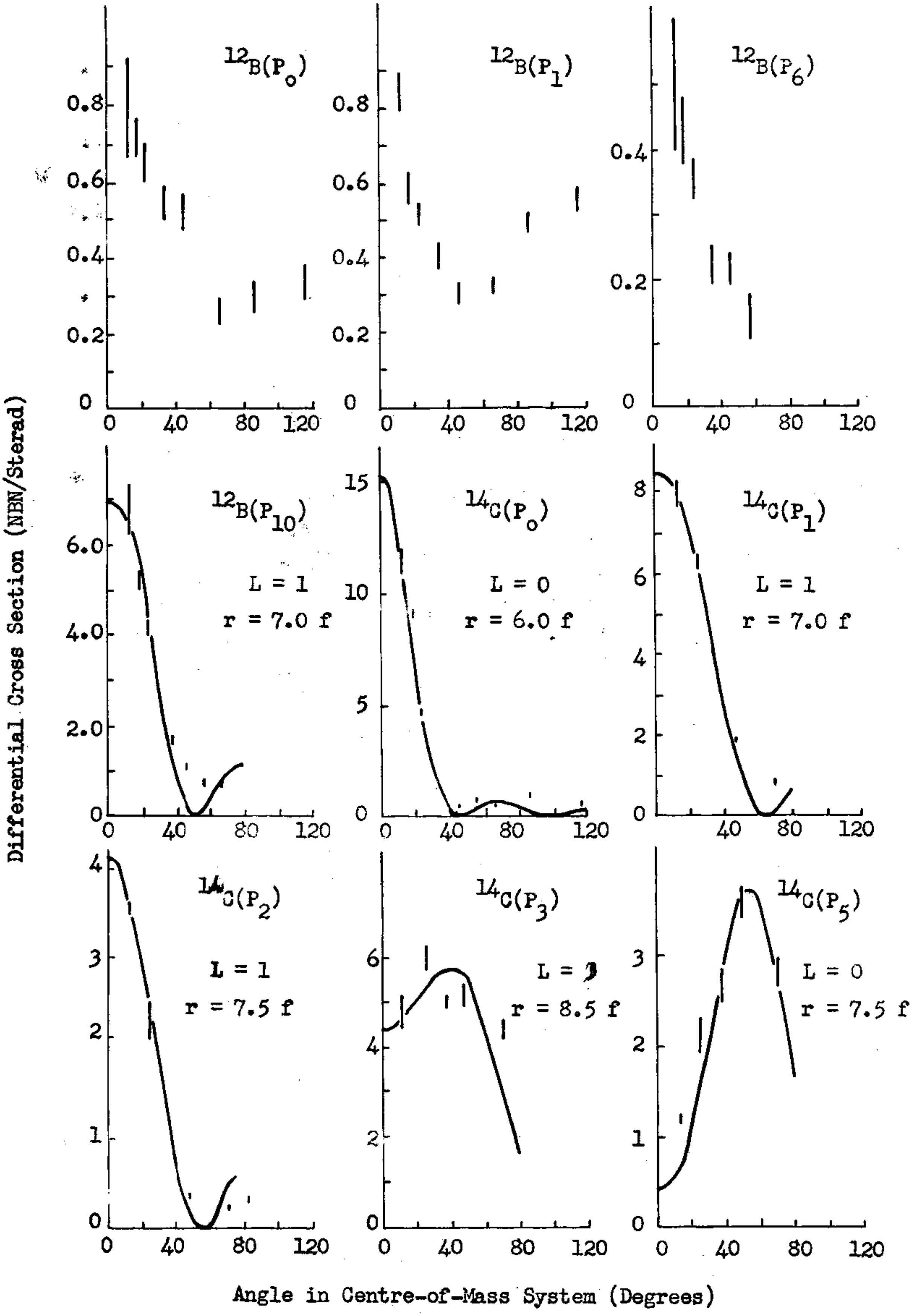
$^{12}B(P_0)$
$^{12}B(P_1)$
$^{12}B(P_6)$
$^{12}B(P_{10})$
L = 1
r = 7.0 f
$^{14}C(P_0)$
L = 0
r = 6.0 f
$^{14}C(P_1)$
L = 1
r = 7.0 f
$^{14}C(P_2)$
L = 1
r = 7.5 f
$^{14}C(P_3)$
L = 3
r = 8.5 f
$^{14}C(P_5)$
L = 0
r = 7.5 f
0
0.2
0.4
0.6
0.8
0
2.0
4.0
6.0
0
5
10
15
0
2
4
6
8
0
1
2
3
4
0
2
4
6
0
40
80
120
Differential Cross Section (NBN/Sterad)
Angle in Centre-of-Mass System (Degrees)

Fig. 2

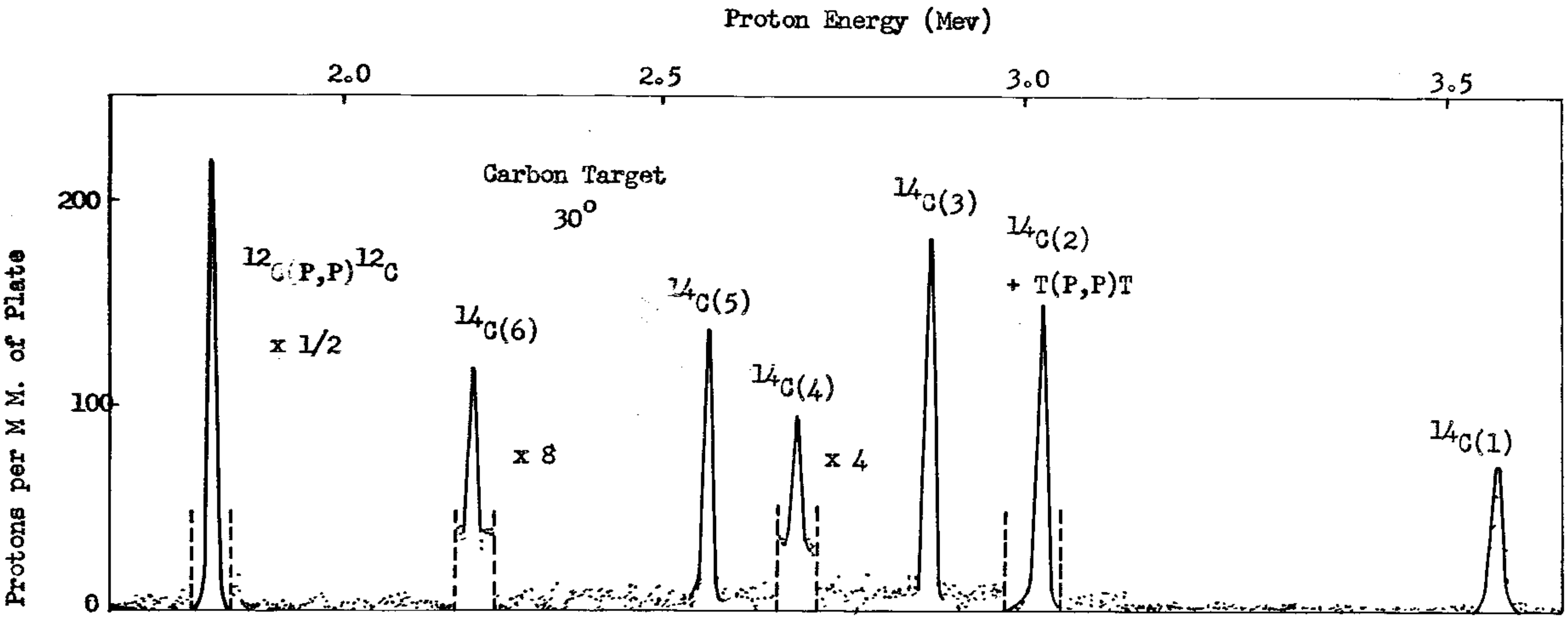
Proton Energy (Mev)
2.0
2.5
3.0
3.5
Protons per M M. of Plate
0
100
200
Carbon Target
30°
$^{12}C(P,P)^{12}C$
x 1/2
$^{14}C(6)$
x 8
$^{14}C(5)$
$^{14}C(4)$
x 4
$^{14}C(3)$
$^{14}C(2)$
+ T(P,P)T
$^{14}C(1)$

Fig. 3

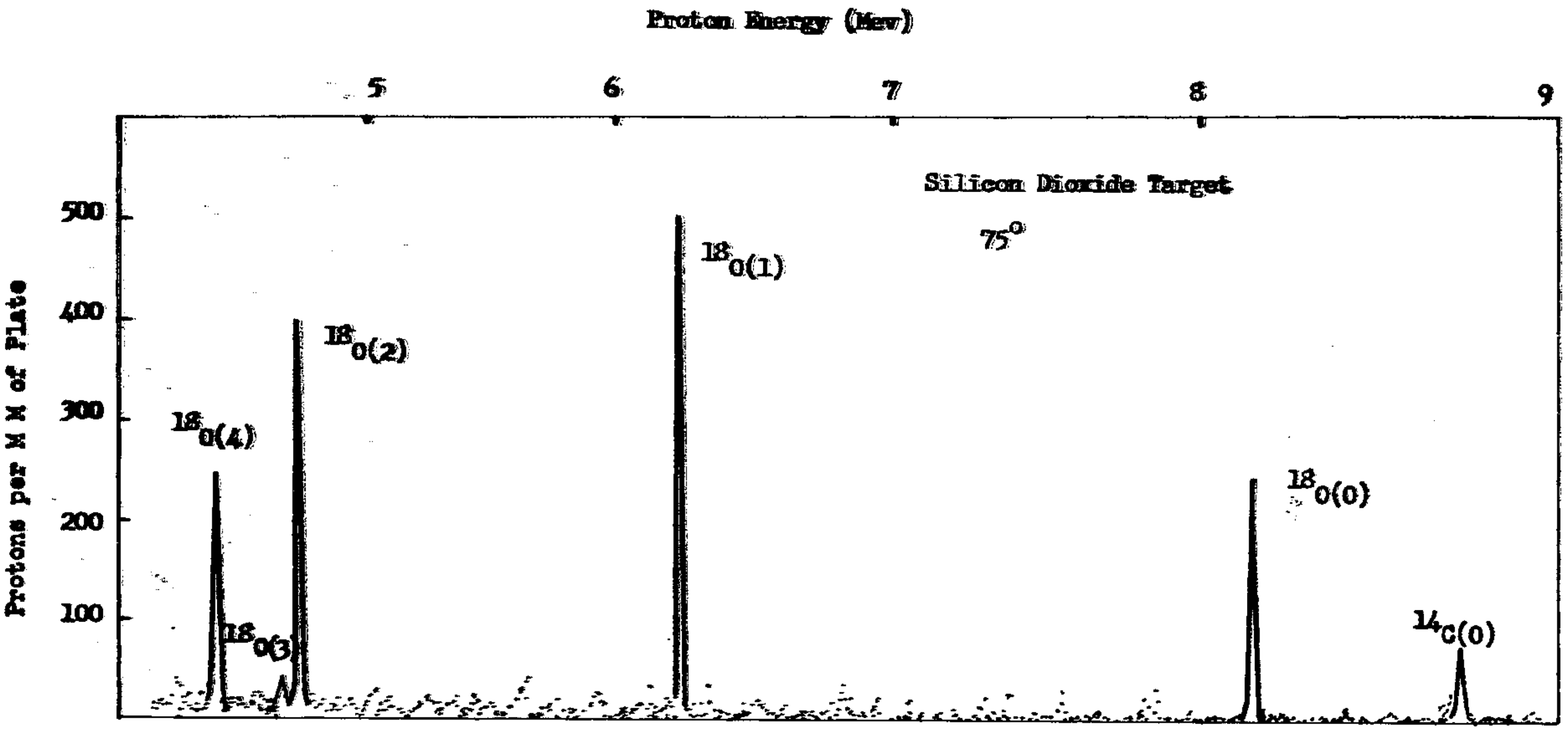
Proton Energy (Mev)
5
6
7
8
9
Silicon Dioxide Target
75°
Protons per M M of Plate
500
400
300
200
100
$^{18}O(4)$
$^{18}O(3)$
$^{18}O(2)$
$^{18}O(1)$
$^{18}O(0)$
$^{14}C(0)$

Fig. 4

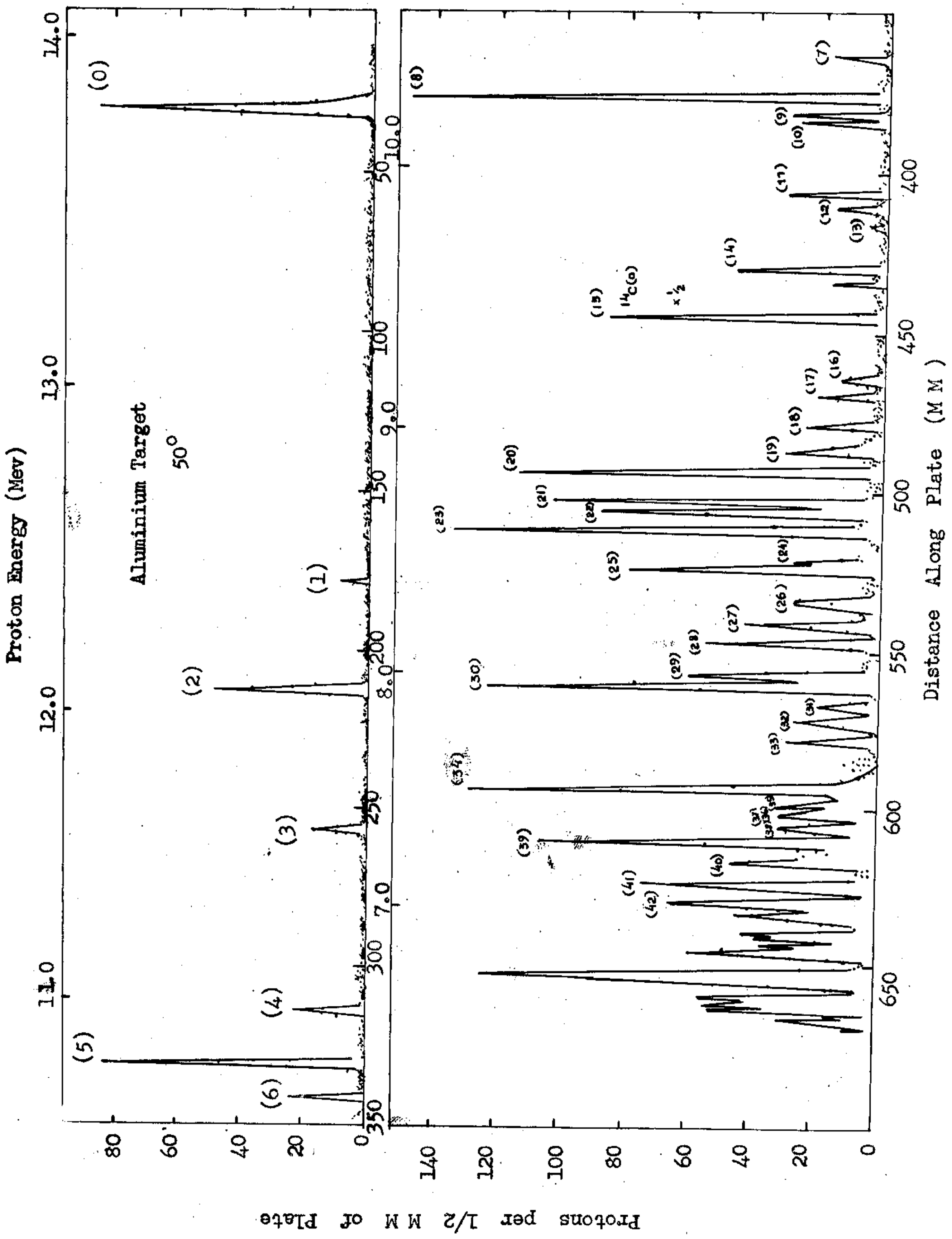
Proton Energy (Mev)
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
Aluminium Target
50°
(0)
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(10)
(11)
(12)
(13)
(14)
(15)
$^{14}C(0)$
x ½
(16)
(17)
(18)
(19)
(20)
(21)
(22)
(23)
(24)
(25)
(26)
(27)
(28)
(29)
(30)
(31)
(32)
(33)
(34)
(35)
(36)
(37)
(38)
(39)
(40)
(41)
(42)
50
100
150
200
250
300
350
400
450
500
550
600
650
0
20
40
60
80
100
120
140
Distance Along Plate (M M)
Protons per 1/2 M M of Plate

Fig. 5

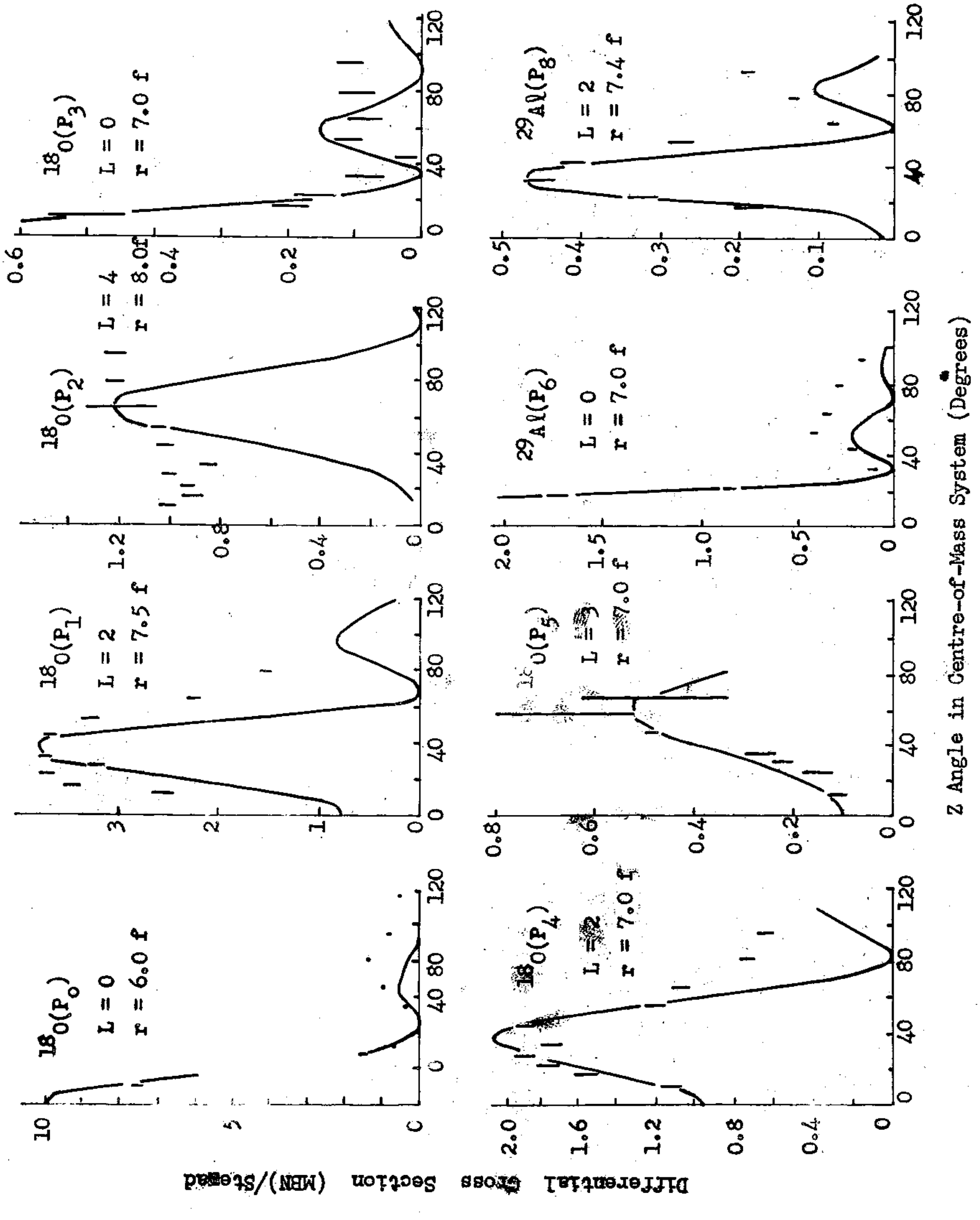
$^{18}O(P_0)$
L = 0
r = 6.0 f
$^{18}O(P_1)$
L = 2
r = 7.5 f
$^{18}O(P_2)$
L = 4
r = 8.0f
$^{18}O(P_3)$
L = 0
r = 7.0 f
$^{18}O(P_4)$
L = 2
r = 7.0 f
$^{18}O(P_5)$
L = 3
r = 7.0 f
$^{29}Al(P_6)$
L = 0
r = 7.0 f
$^{29}Al(P_8)$
L = 2
r = 7.4 f
0
40
80
120
10
5
0
3
2
1
1.2
0.8
0.4
0.6
0.2
2.0
1.6
0.5
1.5
1.0
0.3
0.1
Differential Cross Section (MBN)/Sterad
Z Angle in Centre-of-Mass System (Degrees)

Fig. 6

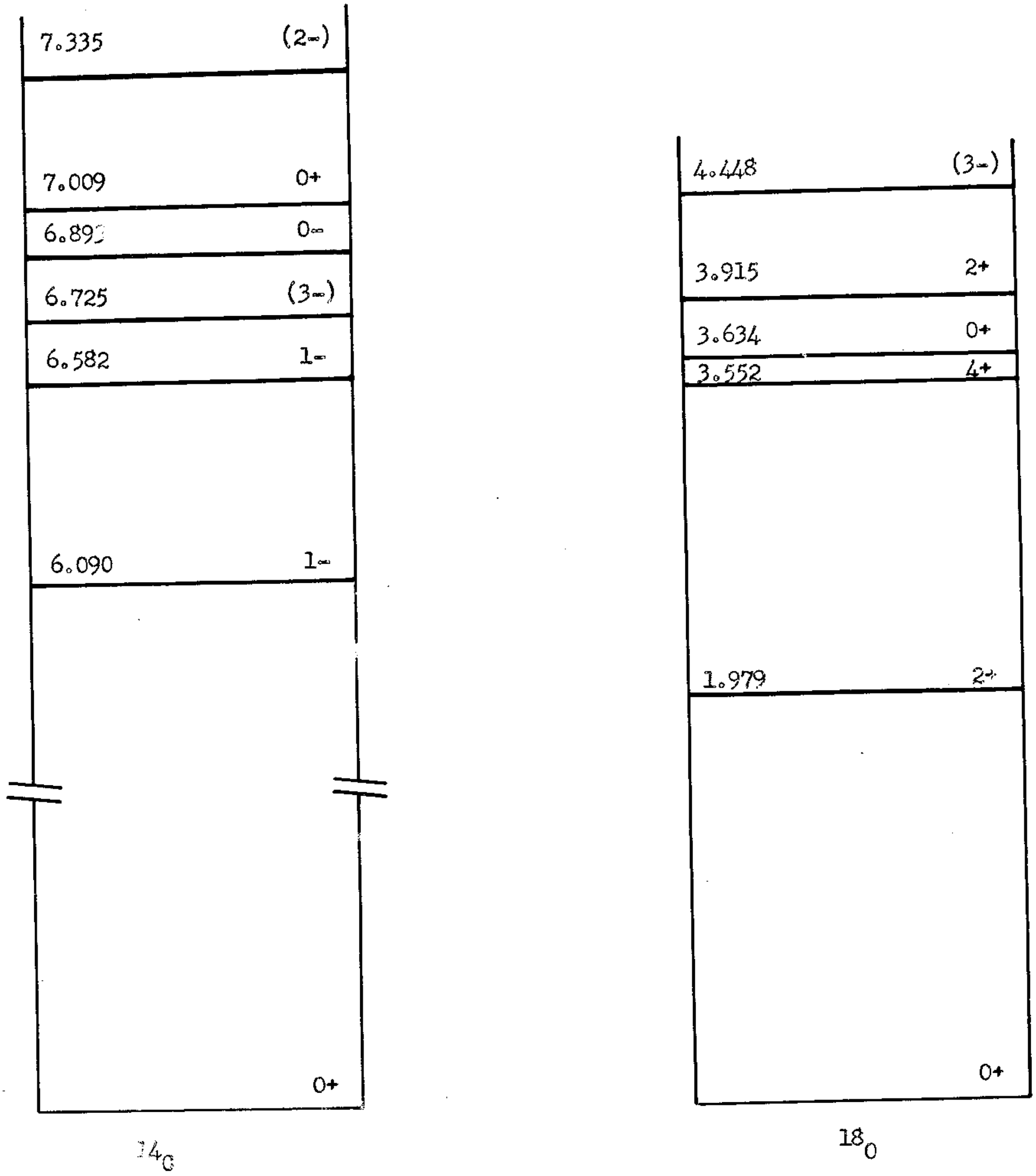
7.335
(2-)
7.009
0+
6.89
0-
6.725
(3-)
6.582
1-
6.090
1-
0+
^{14}C
4.448
(3-)
3.915
2+
3.634
0+
3.552
4+
1.979
2+
0+
^{18}O

Fig. 7

CAPTIONS

Figure 1.

The proton spectrum (at an angle of 20° to the incident beams) from a natural boron target bombarded with 5,5 MeV tritons.

Figure 2.

Angular distributions of some of the proton groups from the reactions ^{10}B(t,p)^{12}B and ^{12}C(t,p)^{14}C.

Figure 3.

The proton spectrum (at an angle of 30° to the incident beam) from the carbon target bombarded with 5.5 MeV tritons.

Figure 4.

The proton spectrum (at an angle of 75° to the incident beam) from the silicon dioxide target bombarded with 5.5 MeV tritons. The group corresponding to the fifth excited state of ^{18}O is too low in energy to be observed on this spectrum; it is present however, on the spectrum shown in figure 2 originating from the oxygen present as an impurity on the boron target.

Figure 5.

The 50° proton spectrum from the ^{27}Al target bombarded with 5.5 MeV tritons.

Figure 6.

Angular distributions of some of the proton groups from the reactions ^{16}O(t,p)^{18}O and ^{27}Al(t,p)^{29}Al.

Figure 7.

The level schemes of the nuclei ^{14}C and ^{18}O, summarising the spin and parity assignments including data derived from the present results.