d,p Reactions from C^{12} and C^{13}†

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Observations have been made of the proton groups resulting from the deuteron bombardment of a carbon target enriched to 60% in C^{13}. A total of twenty-four such groups was observed, of which eleven have been assigned to levels in C^{13} and thirteen to levels in C^{14}. The experimental angular distributions are compared with the predictions of stripping theory. The excitation values for twelve previously unreported levels have been obtained with probable errors of ± 0.02 Mev. These levels are at 7.47, 9.50, and 9.90 Mev in C^{13} and at 6.59, 7.35, 8.32, 9.80, 10.43, 10.50, 12.60, 12.85, and 12.96 Mev in C^{14}.

INTRODUCTION

A STUDY has been made of the $C^{12}(d,p)C^{13}$ and $C^{13}(d,p)C^{14}$ reactions. The apparatus used has been previously described.[1] A collimated beam of 14.8-Mev deuterons is incident upon the target. Outgoing particles are magnetically analyzed and are detected by a CsI(Tl) crystal. Data were obtained at eleven angles lying between 9.8° and 86.6° in the laboratory system. The observed angular distributions are shown and Butler-type calculations are used when possible to determine the angular momentum transfer and parity change of the reactions.

EXPERIMENTAL PROCEDURE

The target used in obtaining most of the data here presented was elemental carbon enriched to 60% in C^{13} and was prepared by cracking methyl iodide on a thin tantalum strip.[2] Targets of natural carbon were used as aids in identifying particle groups and assigning them to the proper isotope. The elemental carbon targets

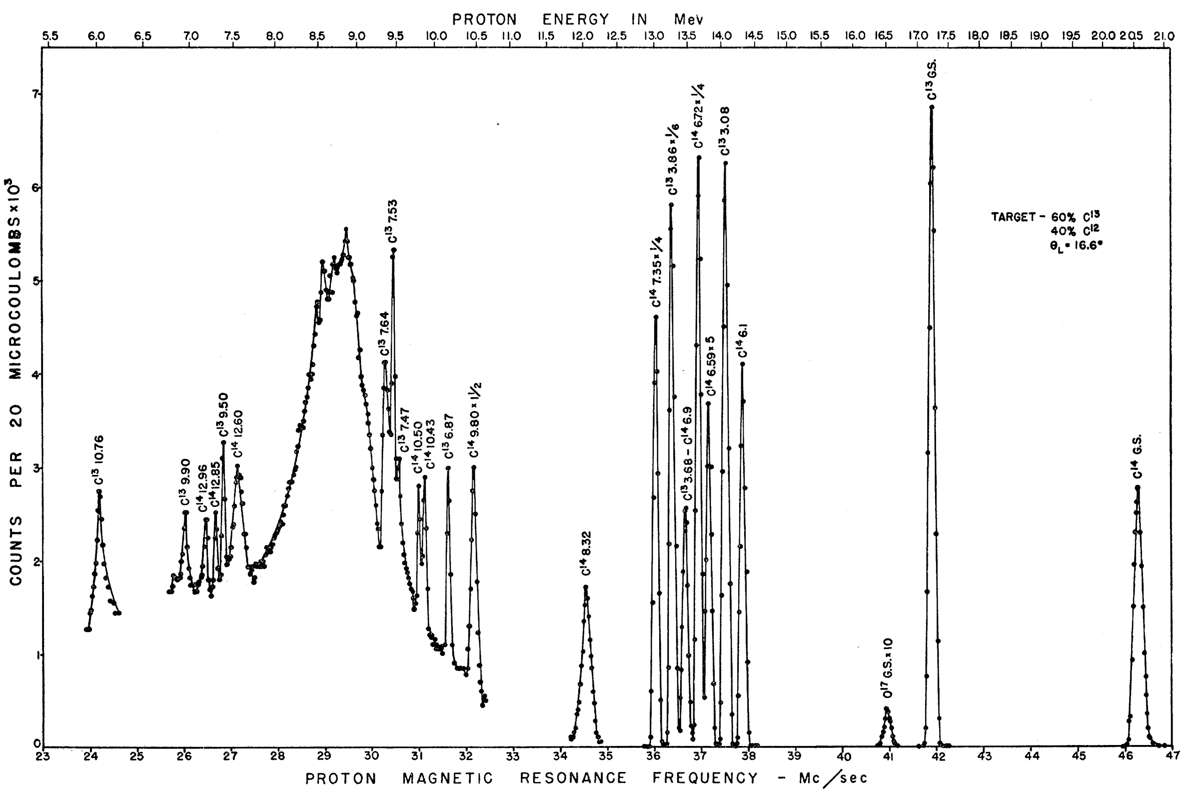

FIG. 1. Proton spectrum observed at 16.6° from a 60% C^{13} target bombarded by 14.8-Mev deuterons. The peaks are labeled by the state of the residual nucleus to which they belong.

† Work done in the Sarah Mellon Scaife Radiation Laboratory and assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] Bender, Reilley, Allen, Ely, Arthur, and Hausman, Rev. Sci. Instr. **23**, 542 (1952); see also Levine, Bender, and McGruer, Phys. Rev. **97**, 1249 (1955).

[2] We are indebted to T. Lauritsen for furnishing the target.

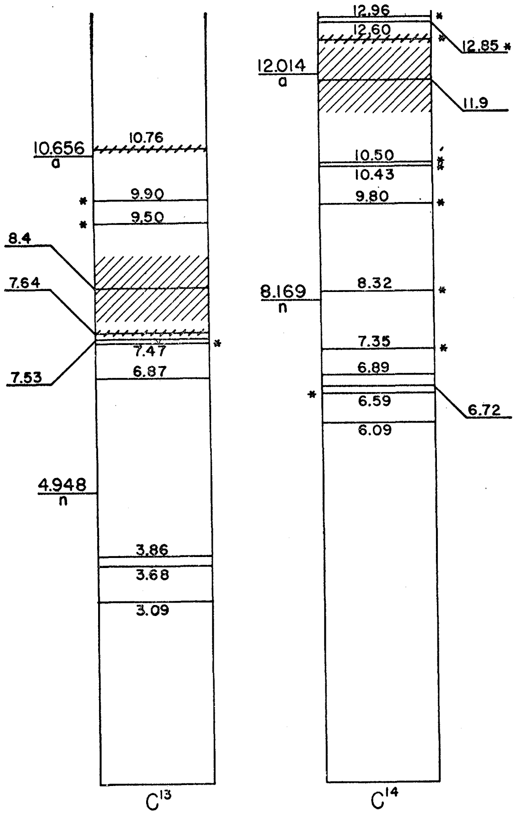

FIG. 2. Energy levels of C^{13} and C^{14} based upon the present work. Levels whose widths are greater than the experimental resolution are cross-hatched. Asterisks denote levels previously unreported.

were self-supporting and showed no sign of deterioration after several hundred hours of bombardment by a 0.5-microampere beam.

The charged particle spectrum observed in survey runs consisted of protons, deuterons, tritons, and α particles. In order to simplify the spectrum, aluminum foils were placed ahead of the detector, their thickness

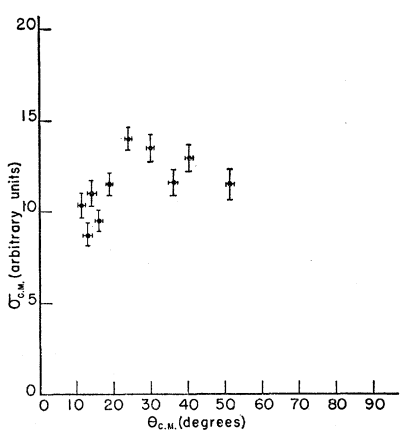

FIG. 3. Angular distribution of the $C^{12}(d,p)C^{13}$ 9.50-Mev level.

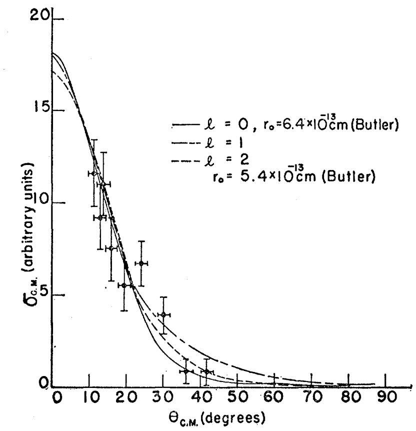

FIG. 4. Angular distribution of the $C^{13}(d,p)C^{14}$ 12.85-Mev level.

being chosen so as to ensure that only protons would be detected.

RESULTS

A. Energy Levels

Figure 1 shows the number of protons observed as a function of the analyzing magnetic field at a laboratory angle of 16.6 degrees. The assignment of the levels to the proper carbon isotope was made by comparing the relative intensities of the proton groups resulting from a natural carbon target (1.1% C^{13}) and from the enriched target. Confirmation of the assignments was possible by measuring the variation in recoil energy with angle. The small proton group appearing at 16.5 Mev in Fig. 1 has been demonstrated to be the O^{17} ground state both by the variation in recoil energy with angle and by the increased intensity of the group upon substitution of an oxygen-containing target (mylar). Figure 2 shows the energy level diagrams of C^{13} and C^{14} based upon the present work. Three previously un-

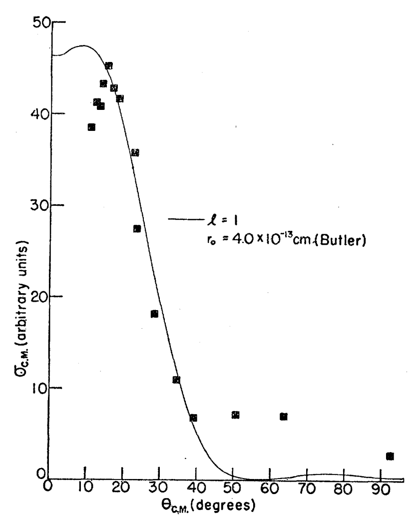

FIG. 5. Angular distribution of the $C^{12}(d,p)C^{13}$ ground state.

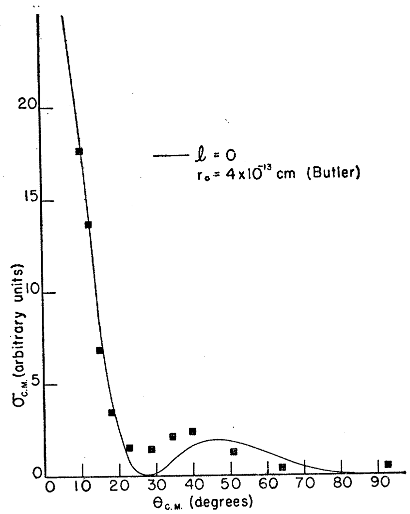

FIG. 6. Angular distribution of the $C^{12}(d,p)C^{13}$ 3.09-Mev level.

reported levels were found in C^{13} and nine in C^{14}. In addition, two levels in C^{13} previously reported[3] at 7.67 and 7.75 Mev are thought to have been more accurately located at 7.53±0.02 Mev and 7.64±0.02 Mev respectively.

The very broad asymmetric proton group shown in Fig. 1 at ~8.75 Mev has been shown to consist of contributions from both $C^{12}+d$ and $C^{13}+d$ reactions by scanning the region with both natural and enriched targets. Both groups are broad, have full widths at half maximum of 1.10±0.3 Mev, occur at the same value of outgoing particle energy, and are of approximately equal intensity. However, since no such structure has appeared in scanning the same region with targets of Ag, Al, or Be, the groups would thus not appear to be instrumental in nature. If they are associated with

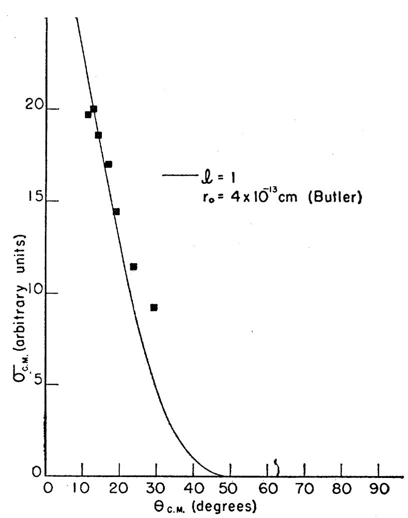

FIG. 7. Angular distribution of the $C^{12}(d,p)C^{13}$ 3.68-Mev level.

[3] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

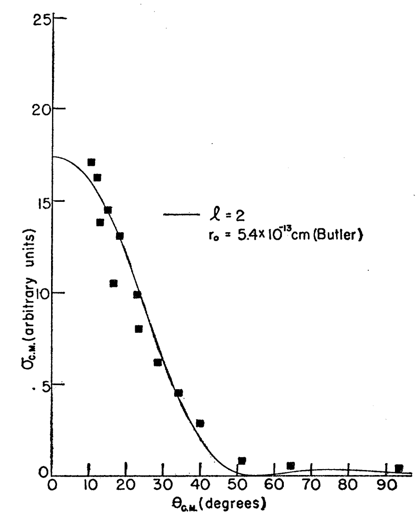

FIG. 8. Angular distribution of the $C^{12}(d,p)C^{13}$ 3.86-Mev level.

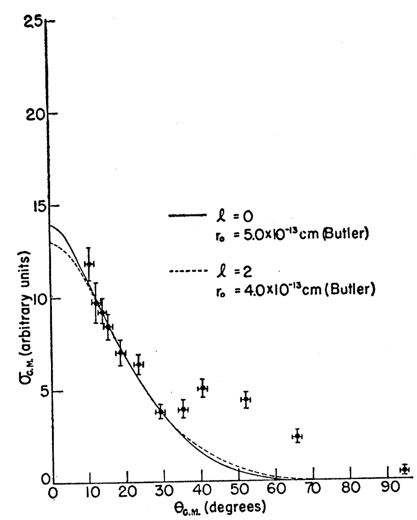

FIG. 9. Angular distribution of the $C^{12}(d,p)C^{13}$ 6.87-Mev level.

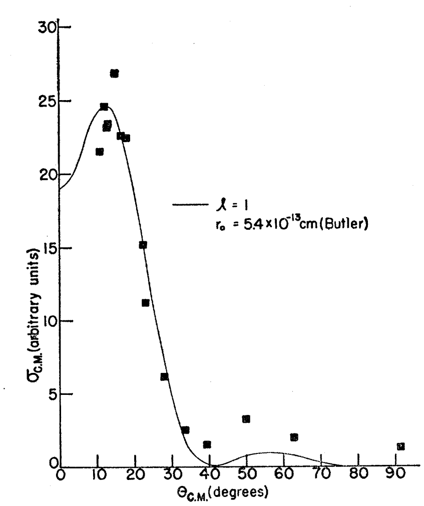

FIG. 10. Angular distribution of the $C^{13}(d,p)C^{14}$ ground state.

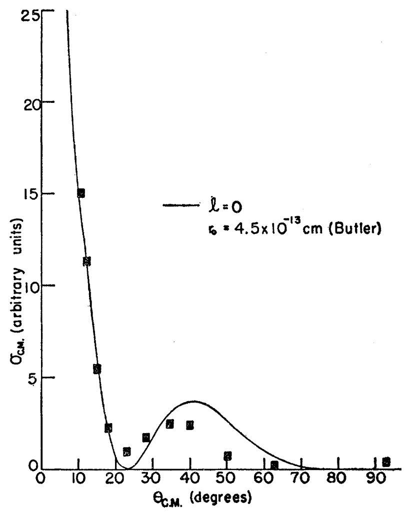

FIG. 11. Angular distribution of the $C^{13}(d,p)C^{14}$ 6.09-Mev level.

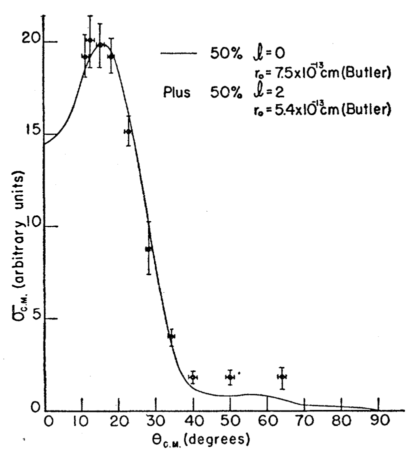

FIG. 12. Angular distribution of the $C^{13}(d,p)C^{14}$ 6.59-Mev level.

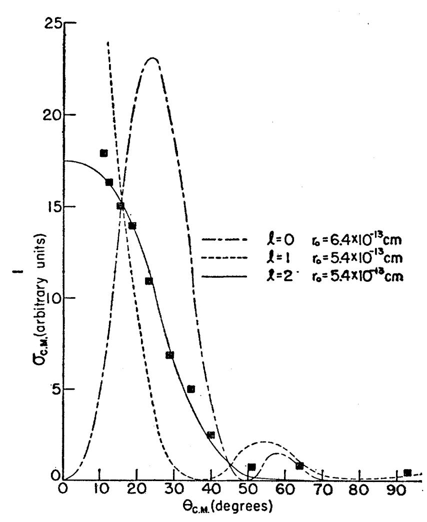

FIG. 13. Angular distribution of the $C^{13}(d,p)C^{14}$ 6.72-Mev level (Butler).

energy levels in C^{13} and C^{14}, they correspond to excitation energies of 8.4 Mev in C^{13} and 11.9 Mev in C^{14}. The angular distributions are strongly peaked in the forward direction; this suggests formation by a stripping process.

Two other levels are observed to have widths greater than the instrumental resolution. These are the C^{13} 7.64-Mev level and the C^{12} 12.60-Mev level which have laboratory widths of 0.070 ± 0.015 Mev and 0.130 ± 0.020 Mev respectively after correcting for instrumental contributions.

B. Angular Distributions

Angular distributions have been obtained for all twenty-four levels observed. All but one have distributions with maxima in the forward direction. The exception is the C^{13} 9.50-Mev level, whose nearly isotropic

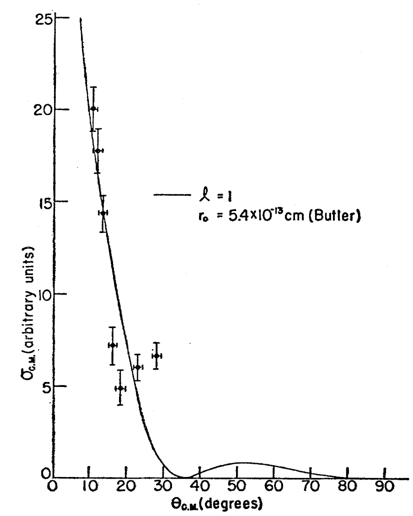

FIG. 14. Angular distribution of the $C^{13}(d,p)C^{14}$ 6.89-Mev level.

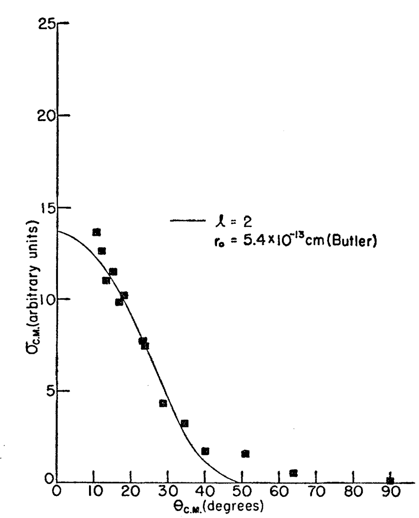

FIG. 15. Angular distribution of the $C^{13}(d,p)C^{14}$ 7.35-Mev level.

TABLE I. Summary of results obtained.

Reaction	E_L (Mev)	Level width (Mev)	l_n	$r_0\times10^{-13}$ cm	Spin$^{(\text{parity})}$ [a]	Spin$^{(\text{parity})}$ [b]	$\sigma(\theta)$ mb/sterad ($\pm50\%$)
$C^{12}(d,p)C^{13}$	0		1	4.0	$1/2^-$	$1/2^-$, $3/2^-$	26
	3.086		0	4.0	$1/2^+$	$1/2^+$	103
	3.685		1	4.0	$3/2^-$	$1/2^-$, $3/2^-$	16
	3.855		2	5.4	$5/2^+$	$3/2^+$, $5/2^+$	152
	6.868		0, 2	5.0, 4.0	$3/2^+$, $5/2^+$	($1/2^+$, $3/2^+$, $5/2^+$)	3.6
	7.470±0.02						~0.8
	7.533±0.02						9.6
	7.641±0.02	0.070±0.015					7.5
	8.4 +0.30	1.10 ±0.30					100
	9.500±0.02						1.6
	9.897+0.02						2.2
	10.759±0.02						4.5
$C^{13}(d,p)C^{14}$	0		1	5.4	0^+	0^+, 1^+, 2^+	10
	6.091		0	4.5	(1^-)	0^-, 1^-	62
	6.589±0.02		0, 2	7.5, 5.4		(0^-, 1^-, 2^-, 3^-)	1.6
	6.723		2	5.4		1^-, 2^-, 3^-	74
	6.894		1	5.4	(0^-)	0^+, 1^+, 2^+	22
	7.346±0.02		2	5.4		1^-, 2^-, 3^-	56
	8.321±0.02						2.2
	9.800±0.02						7.1
	10.433±0.02						~1.9
	10.505±0.02						~1.4
	11.9 ±0.30	1.10 ±0.30					90
	12.601±0.02	0.130±0.020					6.3
	12.854±0.02						1.0
	12.958±0.02						1.9

[a] As given by F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).
[b] Present work.

distribution (Fig. 3) suggests that it is formed through the compound nucleus N^{14}.

Comparison of experimental angular distributions with the stripping theory of Butler can yield information about the orbital angular momentum transfer of the captured neutron (l_n). On the basis of the present work, using 14.8-Mev incident deuterons, stripping theory is usually quite definite in the assignment of l_n to levels having excitations less than the neutron binding energy of the final nucleus. However, for continuum states, the theoretically predicted angular distributions for different values of l_n lie too close together to permit a choice to be made between $l_n=0$, 1, or 2. A typical result for high excitation is shown in Fig. 4, which compares the observed angular distribution of the C^{14} 12.85-Mev level with the theory for $l_n=0$, 1, and 2.

Figures 5 through 9 show the observed angular distributions for the first five states of C^{13}, the solid curves being the Butler curves which best fit the data. For the 6.87-Mev level $l_n=0$ and 2 provided equally good fits. Both are shown in Fig. 9. The C^{13} results are in agreement with previously assigned[3] values of spin and parity for these levels.

A similar comparison of the experimental and stripping distributions is made in Figs. 10 through 15 for the first six states of C^{14}. For most of these levels it was possible to determine l_n unambiguously. Figure 13 compares the observed angular distribution of the C^{14} 6.72-Mev level with the Butler curves for $l_n=0$, 1, and 2. In the case of the C^{14} 6.59-Mev level equally good fits to the data were provided by $l_n=0$ and $l_n=2$. A 50% admixture of the two provided a better fit than either one alone, and is shown in Fig. 12.

The results of the present investigation are summarized in Table I. The values of absolute differential cross section listed are those determined at the forward maximum for those levels which showed maxima, and at the lowest angle of observation ($\theta_L=9.8°$) for those levels whose cross sections were still increasing toward zero angle. Except for the C^{13} 7.47 Mev and the C^{14} 10.43 and 10.50-Mev levels which were not resolved at all angles, the absolute cross sections are uncertain to ±50%, owing chiefly to uncertainty of the target thickness. Relative cross sections are probably good to ±10%. Spin and parity assignments which were arrived at by choosing between not very different stripping curves are shown in parentheses.

We wish to acknowledge the help received from Dr. A. J. Allen and Mr. W. F. Vogelsang during the course of this project.