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Deuteron Capture in C^{14}†

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The cross section for the $C^{14}(d,\gamma)N^{16}$ reaction has been measured in the interval $1.2<E_d<2.6$ MeV by comparing the N^{16} activity with C^{15} activity produced in the (d,p) reaction in the same bombardment. The cross section varies about a value of approximately 5 μb and shows several maxima in the region of bombardment. The results are interpreted in terms of compound-nucleus formation; in particular, for the assumed resonance at $E_d=2.0$ MeV, it is found that $\Gamma\gamma_T\approx 20$ eV. There is no evidence for direct capture, but some contribution from this process cannot be excluded. The half-life of C^{15} was redetermined in the course of the work and found to be 2.49 ± 0.07 sec, a value about 10% higher than that currently accepted.

I. INTRODUCTION

BOTH resonant and nonresonant radiative capture of protons by light elements have been frequently observed and exhaustively analyzed. Resonant radiative capture of α particles has also been observed, for example, in Li^7, C^{12}, and N^{14}.[1] Radiative capture of deuterons has received comparatively little attention, although this process has been observed in several cases (see Table I).

For deuteron bombarding energies up to several MeV, the (d,γ) reaction would be expected to have a relatively small cross section. Direct capture through electric-dipole emission is inhibited by the fact that the captured deuteron (considered as a point) has no dipole moment. If $N=Z$ for the capturing nucleus, direct capture is forbidden. Furthermore, if the (d,γ) reaction takes place through the formation of a compound nucleus as an intermediate step, the radiative process must generally compete with more rapid particle-emission processes. At deuteron bombarding energies on the order of 10 MeV, excitations of the compound nucleus approach the giant-resonance region which is well known from photodisintegration studies. For the case of $N^{14}(d,\gamma)O^{16}$ and $Be^9(d,\gamma)B^{11}$, somewhat lower bombarding energies will form a compound nucleus in the giant-resonance region, and deuteron capture has indeed been reported in these cases (Table I, Ref. d). In the work of Carver and Jones (Table I, Refs. e and f), a giant-resonance shape was assumed in order to calculate cross sections for deuteron capture in Zn^{64}, Cr^{54}, and Ni^{58} at energies somewhat below the giant-resonance peak. The authors find that (d,γ) cross sections in these elements may be accounted for entirely in terms of compound nucleus formation, with no evidence that the cross sections depend on a factor $(N-Z)^2/A^2$, which would arise from direct electric-dipole capture.

TABLE I. Examples of radiative capture of deuterons.

Reaction	Q (MeV)	E_d (MeV)	Cross section	Ref.
$He^3(d,\gamma)Li^5$	16.555	0.45	50 μb	b
$O^{16}(d,\gamma)F^{18}$	7.538	1.7	10 μb	c
$N^{14}(d,\gamma)O^{16}$	20.728	2.26	0.5 ± 0.1 μb/sr[a]	d
$Be^9(d,\gamma)B^{11}$	15.822	1.3	0.62 ± 0.03 μb/sr[a]	d
$Zn^{64}(d,\gamma)Ga^{66}$	10.7	3.5–4.5	27–80 μb	e
$Cr^{54}(d,\gamma)Mn^{56}$	12.9	3.5–4.5	80–295 μb	f
$Ni^{58}(d,\gamma)Cu^{60}$	11.1	3.5–4.5	17–61 μb	f

[a] Observations made at 90°.
[b] J. M. Blair, N. M. Hintz, and D. M. Van Patter, Phys. Rev. **96**, 1023 (1954).
[c] J. W. Butler, Phys. Rev. **99**, 643A (1955): R. Owens and R. G. Winter, (private communication from Dr. Winter).
[d] M. Suffert, D. Magnac-Valette, and J. Yoccoz, J. Phys. Radium **22**, 565 (1961).
[e] J. H. Carver and G. A. Jones, Nucl. Phys. **11**, 400 (1959).
[f] J. H. Carver and G. A. Jones, Nucl. Phys. **24**, 607 (1961).

The cross sections for (d,γ) reactions listed in Table I vary from about 5 to ≈100 μb. In the bombardment of a C^{14} target by deuterons, however, Douglas, Gasten, and Mukerji[2] have observed N^{16} activity which they presumed to come from the $C^{14}(d,\gamma)N^{16}$ reaction. Under this assumption, their calculated yield curve rises smoothly (within experimental error) from about 100 μb to nearly 1 mb in the region $1.0<E_d<3.0$ MeV. This cross section is much higher than that for any other deuteron-capture reactions which have been previously reported and would be difficult to explain on theoretical grounds. Subsequent studies of $C^{14}(d,\gamma)N^{16}$ made in this laboratory[3] showed that the reaction had a cross section of less than 100 μb at $E_d=2.0$ MeV. More recent investigations[4] have shown that the cross section has maximum values of approximately 6 μb in the region $1.2<E_d<2.6$ MeV, and there is evidence for a resonant capture process. This present paper gives a complete account of our recent work on $C^{14}(d,\gamma)N^{16}$.

II. EXPERIMENT

A. Accelerator System

The University of Texas electrostatic generator was used to accelerate deuterons in the energy range from 1.2 to 2.6 MeV. The beam passed through a 90° analyzing magnet and was focused on the target by an electrostatic quadrupole lens. The energy stabilization system regulated spread in energy of the beam to less

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† Assisted by the U. S. Atomic Energy Commission.

[1] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

[2] R. A. Douglas, B. R. Gasten, and A. Mukerji, Can. J. Phys. **34**, 1097 (1956).

[3] J. B. Nelson, E. L. Hudspeth, J. D. Henderson, and I. L. Morgan, Bull. Am. Phys. Soc. **7**, 112 (1962).

[4] J. B. Nelson, E. L. Hudspeth, and E. M. Bernstein, Bull. Am. Phys. Soc. **8**, 598 (1963).

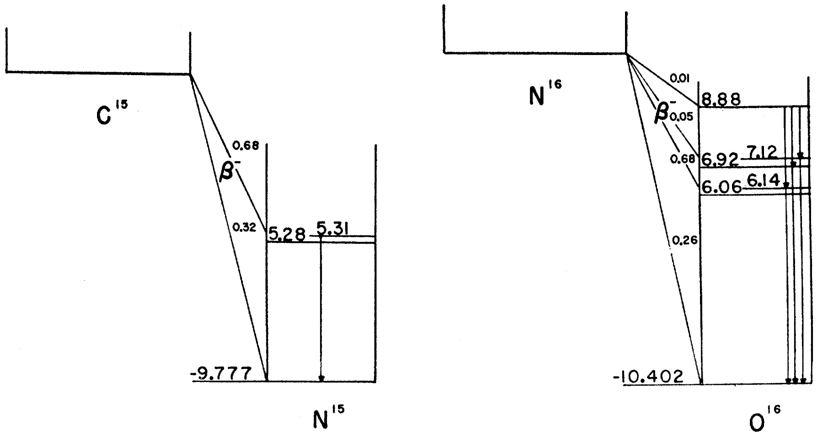

FIG. 1. Comparison of decay schemes for C^{15} and N^{16}. The difficulty of separating the delayed activities arises from the small difference in the energies of the gamma rays.

than ±2 keV. Although higher resolution was obtainable, it was not necessary in this experiment.

B. Targets

Targets of C^{14} in various forms were used in the course of this work. Acetylene (C_2H_2), enriched to an isotopic ratio of 55% in C^{14}, was prepared for us by New England Nuclear Corporation, Boston, Massachusetts, from enriched $BaCO_3$ which was obtained from the Oak Ridge National Laboratory. The acetylene itself was used as a gaseous target in some preliminary bombardments, but self-supporting carbon foils and carbon deposits on gold backings were also used as targets. The foils were prepared in this laboratory from the enriched acetylene by depositing carbon on nickel foil; the nickel was then etched away over a small area, leaving a self-supporting carbon foil.[5] The gold-backed targets were prepared by using gold electrodes in a high-frequency discharge through acetylene.[2] Uniform layers of carbon are thus deposited on the gold, and these targets withstood bombardments by deuteron beams up to 9 μA.

C. Experimental Techniques

One might hope to observe the prompt gamma rays from the excited N^{16} which would be produced by the $C^{14}(d,\gamma)N^{16*}$ reaction. Such an observation must be made, however, in the presence of the gamma rays which are associated with $C^{14}(d,n)N^{15}$ when that reaction leaves the N^{15} excited. Other less troublesome reactions which lead to gamma emission are also present, and the net result is that prompt gamma rays from N^{16} formation will be 0.1% of the total number of gamma rays which come from a bombarded target.

Another possibility is to observe the activity of the product nucleus N^{16}. It was recognized from the outset that difficulty in observing the $C^{14}(d,\gamma)N^{16}$ reaction by measurement of the N^{16} activity would arise from the competing activity of C^{15} produced by $C^{14}(d,p)C^{15}$ and also from the production of N^{16} through the bombardment of impurities. Although N^{16} and C^{15} have quite different half-lives (7.4 and 2.5 sec, respectively), their decay schemes are similar (see Fig. 1). It is impossible to separate cleanly the beta rays from these two isotopes, and the intensity of the delayed gamma rays from N^{16} was expected to be again only 0.1% of the intensity of those from C^{15}. If target impurities include O^{18} or N^{15}, then the reactions $O^{18}(d,\alpha)N^{16}$ and $N^{15}(d,p)N^{16}$ may produce N^{16} in amounts comparable to that produced by $C^{14}(d,\gamma)N^{16}$.

With these facts in mind, we used various techniques in attempts to obtain evidence for the $C^{14}(d,\gamma)N^{16}$ reaction.

1. Initial Investigations

(a) *Gas targets.* It was felt that the problem of target impurities (see above) might be overcome by comparing yields from targets of enriched and of normal acetylene. This gas is easily frozen out of a system, and gaseous impurities could possibly be pumped away. The acetylene was contained in a gas cell 3 cm deep at a pressure of about 40 cm of mercury. It became apparent after several runs that these gas targets would be unsatisfactory since bombardment caused the acetylene to polymerize, leaving a waxy residue in the cell. This is a well-known phenomenon and the effect may be reduced by lowering the cell pressure and the beam current. However, such reductions lead to corresponding decreases in the yield from $C^{14}(d,\gamma)N^{16}$. After some preliminary trials, this approach was abandoned.

(b) *Prompt gamma rays.* The Q value for the formation of N^{16} by deuteron capture in C^{14} is 10.481 MeV. For a deuteron bombarding beam whose energy is 2.0 MeV, we can thus expect prompt gamma rays of approximately 12.2 MeV if the excited state decays directly to the ground level. Less energetic gamma rays would arise from transitions between excited states. Attempts to see these prompt gamma rays with a 3- ×3-in. NaI crystal were thwarted by the large back-

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[5] E. Kashy, R. R. Perry, and J. R. Risser, Nucl. Instr. Methods 4, 167 (1959).

ground produced by the high neutron flux and by gamma rays associated with various (d,n) reactions.

Further attempts[3] were made to observe prompt gamma rays from N^{16} by using the experimental facilities (including an anticoincidence spectrometer and time-of-flight technique) of Texas Nuclear Corporation. Pile-up at the required counting rates hampered this work; however, it was possible to set a rough upper limit on the cross section for the production of prompt gamma rays of energy greater than 11 MeV through de-excitation of N^{16}.

(c) *Search for* N^{16} *recoils.* In an effort to separate the C^{15} produced in the $C^{14}(d,p)C^{15}$ reaction from the N^{16} which may be produced by deuteron capture, thin self-supporting carbon foils were bombarded. N^{16} recoils should proceed directly forward, while C^{15} will be emitted into a cone of increasing angle as E_d is increased. A C^{14}-enriched foil was placed 10 cm in front of a tantalum collector. Immediately following bombardment, the tantalum collector was dropped (without removal from the vacuum system) into a shielded cavity, where its activity was measured. Activity was found, however, with either normal or enriched carbon targets, and was ascribed to bombardment of impurities in the tantalum collector. In spite of the attractive features of this recoil-catcher scheme (which requires very thin targets), it appeared that thicker targets might yield the highest ratio of N^{16} produced from deuteron capture to N^{16} produced through bombardment of impurities.

2. *Measurements of Comparative Activity of Solid Targets*

The method of induced radioactivity was continued, but no attempt was made to separate completely the C^{15} and N^{16} activities. Indeed we sought to compare directly the C^{15} and N^{16} activities produced in the deuteron bombardment of C^{14}, since the $C^{14}(d,p)C^{15}$ cross section is well known from previous work.[2]

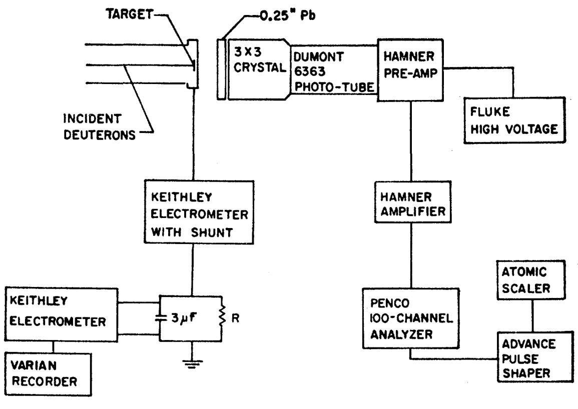

FIG. 2. Block diagram showing arrangement of detecting and counting apparatus. Delayed activity of the target was recorded by using the multichannel analyzer in its time mode. Instantaneous charge on the target was also measured and recorded.

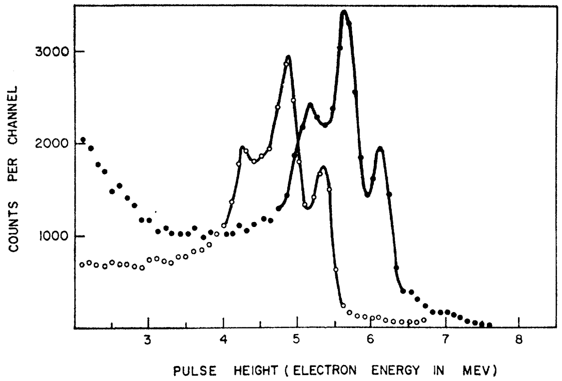

FIG. 3. Spectra of delayed activity produced in a 3- ×3-in. NaI crystal by C^{15} (open circles) and N^{16} (dots). Observed similarity of curves is expected on basis of decay schemes (see Fig. 1); this similarity complicates separation of activities.

The targets for these measurements consisted of carbon deposited on gold backings (see Sec. IIB). The enriched target had a density of 66 μg per square cm, or a thickness of 20 keV for deuterons at 2.0 MeV. The normal target had a density of 103 μg per square cm, or a thickness of 32 keV for deuterons at 2.0 MeV.

The experimental arrangement is shown in Fig. 2. The beam current is integrated using a leaky integrator of the type described by Snowdon.[6] Time constants of the *RC* circuit can be switched to correspond to the decay rate of either C^{15} or N^{16}. The Keithley electrometer output was fed into the Varian recorder and a beam history of each bombardment was made. Pulses from the 3×3-in. NaI crystal were fed into the standard Hamner preamplifier and amplifier arrangement. A Penco 100-channel pulse-height analyzer was employed as a multiscaler and recorded counts as a function of time. The analyzer was advanced one channel when it received a specially shaped pulse originating in the Atomic Instrument Company scaler. The scaler was set to deliver one pulse for every 64 counts at a counting rate of 60 cps, determined by the ac line frequency.

The $C^{14}(d,p)C^{15}$ and $O^{18}(d,\alpha)N^{16}$ reactions were employed to obtain γ-ray spectra from the decay of C^{15} and N^{16}. These are shown in Fig. 3. From these spectra, a bias could be set so that known fractions of both spectra were counted. It appeared that a bias set at 5.1 MeV (see Fig. 3) would be optimum for the following reasons: (1) This value is relatively insensitive to small gain shifts; (2) a large fraction of the N^{16} spectrum is counted; (3) the ratio of counts in the two spectra can be determined with sufficient accuracy. A higher bias would give a more favorable ratio of activities, but the N^{16} counting rate would then be too small.

In our initial runs, the crystal detector was fixed in its counting position near the target during the deuteron bombardment. This arrangement was essentially the same as that used by Douglas *et al.*[2] In attempting to decompose the delayed activity into two components,

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[6] S. C. Snowdon, Phys. Rev. **78**, 229 (1950).

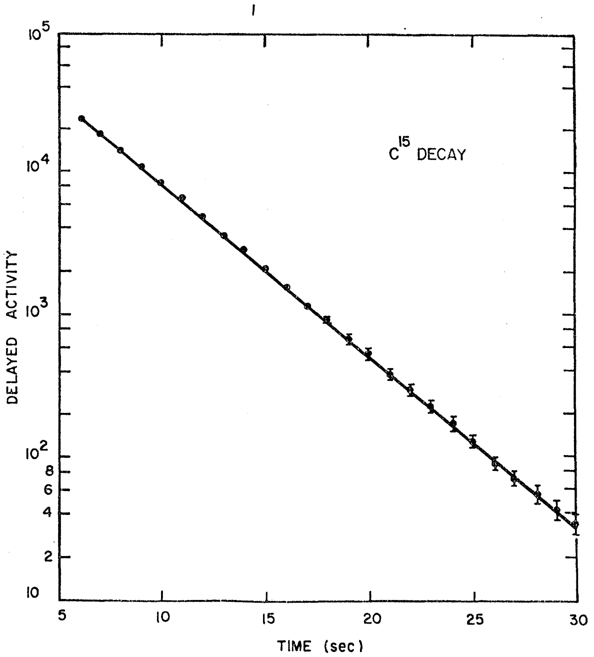

FIG. 4. Activity of C^{15}, produced by $C^{14}(d,p)C^{15}$ reaction at 2.0 MeV. The solid curve represents a half-life of 2.49 sec; a half-life which differs from this by ±0.1 sec leads to curves which lie well outside the error bars associated with the experimentally observed points beyond $t=15$ sec.

using[2] 2.25 sec for the half-life of C^{15} and 7.37 sec for the half-life of N^{16}, it became apparent that a third activity was present with a half-life comparable to but somewhat greater than that of N^{16}. The intensity of this activity was in fact much greater than that of N^{16}. We attribute this activity to F^{20}. At $E_d=2.0$ MeV, the neutrons produced by $C^{14}(d,n)N^{15}$ have maximum energies in the 10-MeV range; these neutrons may in turn react with the Na^{23} in the detector and produce[7] F^{20}. The F^{20} decays by β emission to the 1.63-MeV level in Ne^{20}, which decays promptly to the ground state. The β end-point energy is 5.32 MeV, and the half-life of F^{20} is 11.2±0.1 sec.[8] Hence a bias which is set to record electron-energy deposition of 5.1 MeV in the crystal will allow detection of β-γ decays of F^{20} if the β ray has an energy greater than about 3.5 MeV. (When the bias was lowered to 4.3 MeV, it was found that the yield of the 11.2-sec activity showed the expected increase.) Douglas *et al.*[2] assumed only two components in their decay curve—one due to C^{15} decay and the other due to N^{16}—since the longer lived component could be fit within their statistical errors to the known 7.37-sec half-life of N^{16}. Inasmuch as our initial experimental arrangement was very similar to theirs, it appears almost certain that most of the longer lived activity which they observed was due to F^{20}. This assumption would explain why their determination of the half-life of C^{15} is somewhat lower than we subsequently found (see below) and also why their reported values for the $C^{14}(d,\gamma)N^{16}$ reaction are much larger than those we shall report here.

In order to reduce the amount of F^{20} produced in the NaI crystal, a ramp was constructed to slide the detector away from the target during the bombardment. The detector was held approximately 9.5 ft from the target, decreasing the neutron flux through it during bombardment by a factor of 10^4. A solenoid-activated catch, which released the crystal, was energized simultaneously with beam cutoff. A 4-sec interval was required for the detector to slide down the ramp, decelerate and seat itself behind the target.

Analysis of our data requires that the half-life of C^{15} be known quite accurately. With the F^{20} activity eliminated, it was possible to make an accurate determination of the C^{15} half-life. The following steps were taken in order to check the consistency of our measurements:

(1) The accuracy of the time scale was confirmed by observing the half-life of N^{16} produced in the reaction $O^{18}(d,\alpha)N^{16}$, using a $BaCO_3$ target enriched in O^{18}; our measured value of 7.25±0.10 sec was in agreement with the reported value of 7.37±0.04 sec.[1]

(2) Measurements were made for several energies of deuteron bombardment.

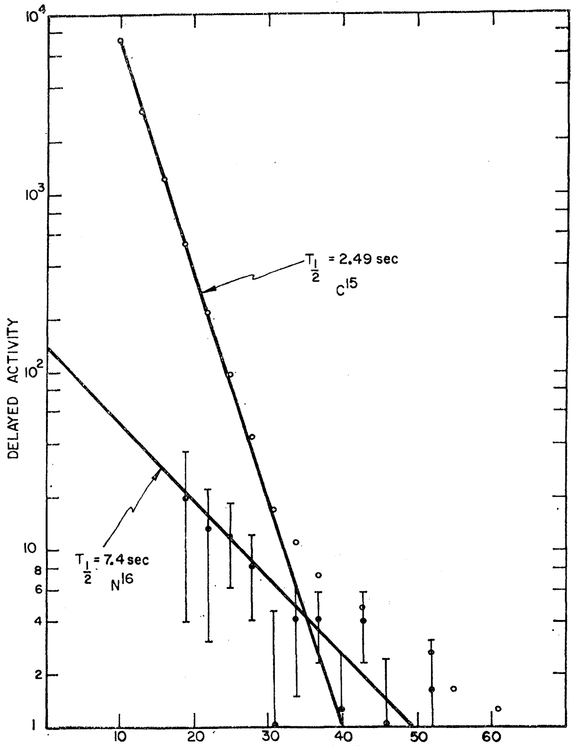

FIG. 5. Plot of an analysis of delayed activity obtained from a C^{14} target with 2.0-MeV deuterons. The two activities are ascribed to C^{15} and to N^{16}.

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[7] C. F. Williamson, Phys. Rev. 122, 1877 (1961).

[8] G. Scharff-Goldhaber, A. Goodman, and M. G. Silbert, Phys. Rev. Letters 4, 25 (1960).

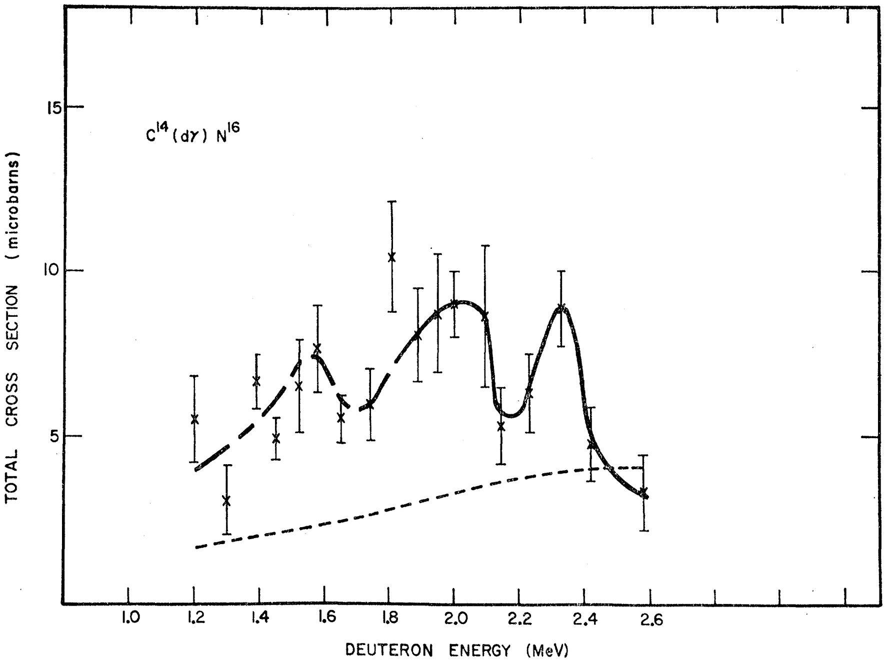

FIG. 6. Excitation curve for the $C^{14}(d,\gamma)N^{16}$ reaction. The heavy curve was obtained from bombardment of a carbon target containing 55% C^{14}. The lower (dashed) curve was obtained by bombardment of a normal carbon target. Normalization was affected as described in text.

(3) The beta decay of C^{15} was observed with a plastic scintillator as detector.

(4) Various window settings were placed on the NaI detector.

All of our observations were consistent with a C^{15} half-life of 2.49 ± 0.07 sec. A typical decay curve is shown in Fig. 4.

The following procedure was employed to obtain the cross section for $C^{14}(d,\gamma)N^{16}$:

(1) The counting system was calibrated with a ThC″ source and the 5.31-MeV gamma ray from the decay of C^{15}. The desired bias settings were made and the decay constant set on the leaky integrator. The beam-history recorder was turned on.

(2) The deuteron beam was brought on the target at the desired energy, starting the irradiation.

(3) When the charge on the leaky integrator neared saturation, indicated by an almost constant voltage reading, the bombarding beam was interrupted by switching off the $B+$ for the ion-source oscillator in the terminal. This eliminated background from the electrostatic generator.

(4) The advance-pulse electronics for the multiscaler were started simultaneously with beam interruption. The NaI detector was released and allowed to slide down the ramp.

(5) The beam-history recorder was turned off. The multiscaler stopped counting when it reached channel 100. The data were printed on tape.

(6) Individual points taken at a specific energy, over a period of several days, were averaged together. In order to minimize any systematic effects of impurity buildup on the target, the incident deuteron energy for any single run was chosen in a random manner.

To determine the amount of N^{16} present at the end of a bombardment, the following procedure was employed to analyze the data:

The time interval from 25 to 60 sec after beam interruption was most sensitive to the amount of N^{16} produced (see Fig. 5). The expected C^{15} contribution in the 25 to 60-sec interval was calculated, assuming the initial counts were due to C^{15}. The sum of this C^{15} contribution and the background (obtained by following activity beyond 60 sec) was then subtracted from the total number of N^{16} decays in this time interval. The amount present at $t=0$ was easily calculated from a knowledge of gate settings, the decay scheme for N^{16}, and the time record of the deuteron beam.

Although our observations of delayed activity were analyzed as described in the preceding paragraph, we also made numerous plots to check our results. A typical plot is shown in Fig. 5.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The yield curves from both the normal and enriched targets in the region $1.2<E_d<2.6$ MeV are shown in Fig. 6. Each point which comprises the yield curve for the enriched target represents the average value of from three to five individual measurements taken over a period of several days. The statistical errors in the data obtained at $E_d<1.6$ MeV make the excitation curve somewhat uncertain in that region.

The excitation curve for the normal target is represented by the lower dashed line in Fig. 6. The activity of the N^{16} produced in the normal target could be

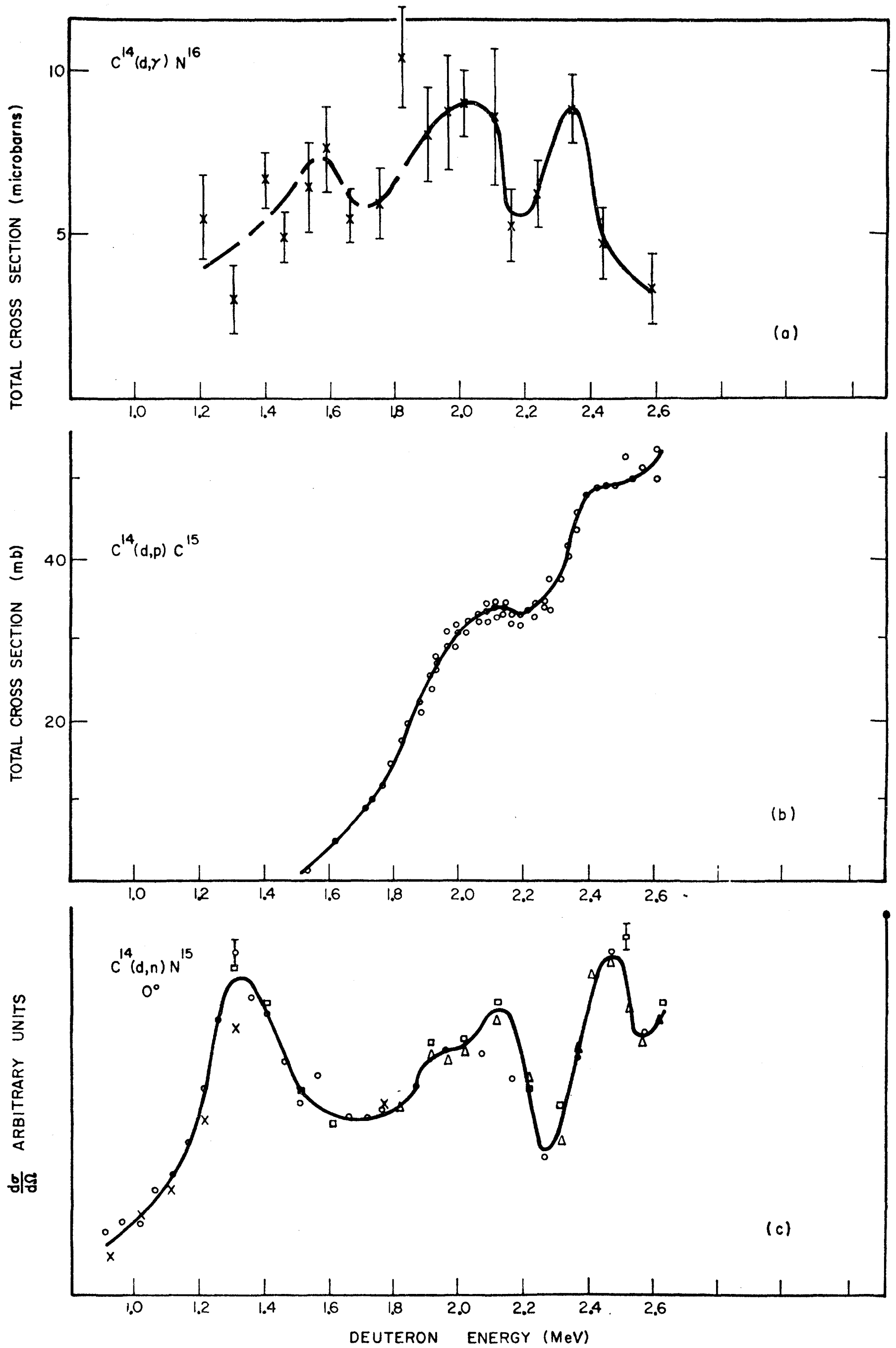

FIG. 7. Comparison of excitation curves for $C^{14}(d,\gamma)N^{16}$, $C^{14}(d,p)C^{15}$, and $C^{14}(d,n)N^{15}$ (ground state). All three curves indicate at least two maxima beyond $E_d=1.8$ MeV. Curve (a) is from the present work (see Fig. 6); curve (b) is drawn from Ref. 2. Curve (c) represents a series of unpublished observations by Dr. C. E. Brient of this laboratory (see also Ref. 9).

determined rather accurately, since there is no interfering activity from C^{15}.

Since the 7.4-sec activity is observed on both the normal and the enriched targets, we assume that contaminants cause a portion of the activity detected after the deuteron bombardment of C^{14}. It is known that carbon absorbs oxygen and nitrogen from the atmosphere. The deposition process, however, was identical for both targets. Thus, it is not unreasonable to assume the same contaminant will be found in the enriched and normal targets and the amount will be proportional to the target weight. If one assumes that the contamination is contained on the surfaces of the targets and is therefore nearly independent of target weight, then the N^{16} activity for the normal target (as shown in Fig. 6) should be reduced by a factor of 66/103 before subtracing it from the activity of the enriched target.

A comparison of the excitation curve obtained with the normal target to the excitation curve for the $N^{15}(d,p)N^{16}$ reaction[9] shows some similarity. However, it is most probable that the interfering contaminant is a mixture of O^{18} and N^{15}.

Figure 7 compares the excitation curves for the $C^{14}(d,\gamma)N^{16}$ reaction and two other deuteron-induced reactions in C^{14}, vis., the $C^{14}(d,p)C^{15}$ reaction[2] and the $C^{14}(d,n)N^{15}$ reaction.[10] The existence of maxima at certain energies in the excitation curves supports the assumption that compound nucleus formation is involved in the reactions. A maximum is found at approximately 2.0 MeV in each case. The maximum observed at $E_d \approx 2.35$ MeV for the $C^{14}(d,\gamma)N^{16}$ reaction occurs at a somewhat lower energy than the maxima reported in the $C^{14}(d,p)C^{15}$ and $C^{14}(d,n)N^{15}$ reactions, but it is difficult to compare the positions of the peaks accurately.

Figure 6 shows that the cross section for the $C^{14}(d,\gamma)N^{16}$ reaction varies about a value of approximately 5 μb in the region $1.5 < E_d < 2.5$ MeV. It is interesting to compare this cross section with that tentatively reported by Winter and Owen (Table I, Ref. c) for the $O^{16}(d,\gamma)F^{18}$ reaction. Their excitation function rises rapidly beyond $E_d \approx 0.5$ MeV (where the yield was first measurable) and lies between about 8 and 16 μb in the region $1.5 < E_d < 2.5$ MeV. If direct capture is of importance in the $C^{14}(d,\gamma)N^{16}$ and $O^{16}(d,\gamma)F^{18}$ reactions, then the cross sections would be expected to show a dependence on $(N-Z)^2/A^2$ (see Introduction). This mechanism would contribute nothing in the O^{16} case, but in point of fact the measured cross section is actually greater for $O^{16}(d,\gamma)F^{18}$ than for $C^{14}(d,\gamma)N^{16}$. This lack of appreciable dependence on $N-Z$ agrees with the results obtained by Carver and Jones (Table I, Ref. f) in their studies of deuteron capture in heavier elements.

Winter and Owens (Table I, Ref. c) have compared their experimental measurements of the $O^{16}(d,\gamma)F^{18}$ cross section with calculations which they have made on the basis of estimates for compound nucleus formation. They conclude that $\Gamma_\gamma/\Gamma_{\text{particle}}$ is 10^{-5} in order of magnitude, a reasonable result and one which is in agreement (see following paragraph) with our analysis of the $C^{14}(d,\gamma)N^{16}$ cross section.

If one assumes compound nucleus formation in the reaction $C^{14}(d,\gamma)N^{16}$, the partial width for prompt gamma emission from excited N^{16} may be estimated from the following considerations. The cross section for the $C^{14}(d,p)C^{15}$ reaction at 2.0 MeV is approximately 10 mb (excluding stripping),[2] and the resonance reported there has a total width of 270 keV.[2] The $C^{14}(d,n)N^{15}$ cross section for production of ground-state neutrons[10] is estimated (after subtracting the estimated stripping contribution) as ≈ 20 mb; on the basis of rough data[11] at $E_d = 1.26$ MeV, this is increased by a factor of 3 to include neutrons of lower energies. The $C^{14}(d,\alpha)B^{12}$ and compound elastic scattering may, for this rough calculation, be ignored. It is therefore concluded that the cross section for compound nucleus formation is 70 mb, within a factor of perhaps 2. If the measured cross section for gamma emission is taken as 5μb at $E_d = 2.0$ MeV, then the sum of the partial widths for gamma emission is $\Gamma_{\gamma T} \approx 20$ eV. This is in agreement with partial widths which have been measured in cases of proton and alpha capture; it lies well within the limits of Wilkinson's empirical modification[12] of the Weisskopf single-particle shell-model predictions. Further analysis seems unwarranted, in view of the lack of knowledge of the decay scheme and of the various states of N^{16*}.

A theoretical excitation function for the $C^{12}(d,\gamma)N^{14}$ reaction ($Q = 10.265$ MeV) has been calculated by Dr. V. A. Madsen.[13] The calculation is based on the direct 2-stage (stripping, capture) mechanism which was developed for studying (γ,d) reactions.[14] The cross section rises from approximately 5 μb at $E_d = 2$ MeV to a maximum of 8 μb at 5 MeV, and then falls gradually to ≈ 2 μb at 20 MeV. The calculated cross section at 2 MeV is very close to that which we have found for the $C^{14}(d,\gamma)N^{16}$ reaction. However, from the shape of our excitation function, it appears that no more than one-half the yield could be due to a direct process, which presumably would vary smoothly with energy. On the basis of the very limited experimental data on (d,γ) reactions, no quantitative conclusions may be drawn.

IV. CONCLUSIONS

The $C^{14}(d,\gamma)N^{16}$ reaction has been observed in a region of deuteron bombardment from 1.2 to 2.6 MeV. The cross section varies around a value of approximately 5 μb in that region, and there is strong evidence for resonances in the excitation curve. The resonant bombarding energies apparently correspond in at least two cases to those found in the competing (d,n) and (d,p) reactions.

The results of our measurements of the cross section for deuteron capture may be interpreted in terms of compound nucleus formation. There is no evidence for direct capture; however, some contribution from this process cannot be excluded.

The half-life of C^{15} (redetermined in the course of analyzing our data) was measured as 2.49 ± 0.07 sec.

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[9] N. A. Bostrom, E. L. Hudspeth, and I. L. Morgan, Phys. Rev. **105**, 1945 (1957).

[10] R. Chiba, Phys. Rev. **123**, 1316 (1961).

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