Excitation Curve for $C^{14}(d,p)C^{15}$ and Properties of C^{15}†

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The excitation function for $C^{14}(d,p)C^{15}$ has been studied with deuterons of energy 0.6 to 3.0 Mev. A previously suspected resonance was definitely established at a bombarding energy of 2.15 Mev, with a width of nearly 400 kev. Analysis of the excitation curve shows that its shape may be explained on the basis of a spin of 5/2(+) for the C^{15} ground state and a Q value of 0.15 ± 0.15 Mev. This leads to a mass of C^{15} of 15.0141 $\pm$0.00015 amu.

I. INTRODUCTION

THE isotope C^{15} has been observed previously[1,2] as a product of deuteron bombardment of C^{14}. It has a half-life of 2.4 seconds, and it is known that the decay of this nucleus yields β rays of maximum energy nearly 8.8 Mev and that delayed γ radiation of energy approximately 5.5 Mev[3] (with possibly other components) is present. The Q value for $C^{14}(d,p)C^{15}$ has not previously been established, since the decay scheme of C^{15} is not definitely known and the protons from the reaction have not been observed thus far. It is certain, however, that the 8.8-Mev β rays cannot be in coincidence with the observed 5.3-Mev γ rays; if such were the case, C^{15} would be unstable against heavy particle emission. An excitation curve for $C^{14}(d,p)C^{15}$, based on nine bombarding energies in the range 1.4 to 2.8 Mev, has been reported,[2] and the existence of one resonance in this region (near 2 Mev) was thought probable.

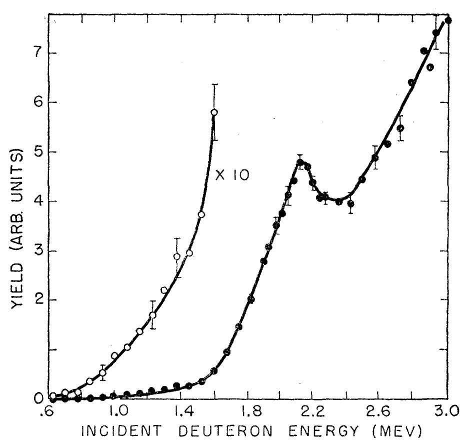

FIG. 1. Experimentally observed excitation curve for $C^{14}(d,p)C^{15}$. Target thickness about 15 kev for 1-Mev deuterons.

The work described herein was directed toward two primary purposes: (1) to obtain a more accurate excitation curve for $C^{14}(d,p)C^{15}$ over a broader energy interval of bombarding deuterons, including especially the low-energy region; and (2) to analyze the resultant curve in order to determine the Q value for the reaction and to deduce the probable value for the spin of C^{15}. The experimental work described herein has been briefly reported,[4] and some additional analysis is included in this note.

II. EXPERIMENTAL PROCEDURE

The Van de Graaff generator at the University of Texas was used in these experiments for the bombardment of a $BaCO_3$ target, enriched 18.6 percent in C^{14}. A uniform target was prepared by painting a thick slurry of water and $BaCO_3$ on a silver disk. The target used in most of the present work had a weight of 0.124 mg/cm^2, or a thickness of about 15 kev for 1-Mev deuterons.

The deuteron beam was regulated to about 0.3 percent by a slit system and probe current control; higher resolution is possible but was not considered necessary in this experiment.

The activity of the target was measured by a scintillation counter. A sodium iodide crystal was used in conjunction with a 5819 photomultiplier tube, a linear amplifier, pulse height selector, and appropriate scaling and counting circuits.

Deuteron bombardment of $BaCO_3$ results in the formation of several radioactive nuclides, including B^{12}, N^{13}, and F^{17}, as well as C^{15}. (F^{17} is produced only at bombarding energies greater than about 1.6 Mev.) A bombarded target also emits neutrons and γ rays from excited states of stable elements, but ordinarily these are emitted almost instantaneously. It is most convenient to measure the activity of C^{15} in the presence of the other radioactive nuclides by bombarding the target for a known time with a known current, stopping the bombardment and allowing the B^{12} (of half-life only about 25 milliseconds) to decay almost entirely, and then to begin counting the radiations from C^{15}. This was accomplished by setting the pulse-height selector so as to discriminate against radiation which

† Experimental work assisted by the U. S. Atomic Energy Commission; the analysis was assisted by the Office of Scientific Research of the Air Research and Development Command.
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[1] Hudspeth, Swann, and Heydenburg, Phys. Rev. 77, 736 (1950).
[2] Hudspeth, Swann, and Heydenburg, Phys. Rev. 80, 643 (1950).
[3] Hudspeth, Rose, and Heydenburg, Phys. Rev. 85, 742(A) (1952). The first excited state in N^{15} consists of a doublet near 5.3 Mev; we therefore assume that this is a more precise value for the energy of the delayed γ radiation.
[4] J. A. Rickard and E. L. Hudspeth, Austin Meeting of the American Physical Society [Phys. Rev. 94, 806 (A) (1954)].

was less energetic than about 2 Mev, leaving only the C^{15} activity and a small cosmic-ray background. The final evidence for the validity of the methods of timing and discrimination came from an inspection of the counting rate, which was observed to decline in the manner expected of 2.4-seconds half-life activity.

The yield of both the 8.8-Mev β rays and the 5.3-Mev γ rays from C^{15} was measured with the sodium iodide scintillation counter. By taking counts with and without various shields, it was found that the number of counts caused by β rays was approximately the same as that caused by the γ rays. The equal magnitude measurement is not particularly significant, being a function of the relative efficiency of the counting equipment for detecting β and γ radiation and of the discriminator setting, but the fact that the curves were identical in shape made it possible to improve statistical accuracy by measuring both types of radiation simultaneously. The data represented by the excitation curve of Fig. 1 were taken in this manner.

In obtaining points on the excitation curve, the following steps were taken: (1) The beam of the statitron was turned on and allowed to continue for a 30-second time interval, during which the number of beam integrator counts was recorded; (2) at the end of the chosen time interval, the high voltage on the statitron was cut off (by stopping the spray-on current), an interrupter was pushed into the deuteron beam, and, after about 0.1 second (to allow decay of B^{12} formed during bombardment), the scintillation counter was allowed to feed into a scaler for twenty seconds. This 20-second interval represents about eight half-lives of C^{15}, and hence the decay was virtually complete.

Table I. Possible l values.

Spin of 1/2(+) Deuterons	Protons	Spin of 5/2(+) Deuterons	Protons
$l=0$	$l'=0$	$l=0$	$l'=2$
0	2	1	1
1	1	2	0
2	0		

III. RESULTS AND DEDUCTIONS

The experimental excitation curve for $C^{14}(d,p)C^{15}$ is shown in Fig. 1. The existence of the suspected resonance at a bombarding energy of about 2 Mev is confirmed.

Figure 2 shows the resonance in N^{16} in greater detail. This curve was obtained by the graphical subtraction of a postulated smooth excitation curve from the observed curve in the resonance region. The peak is estimated from the graph to lie at 2.15-Mev bombarding energy, which corresponds to an excitation of 12.8±0.5 Mev

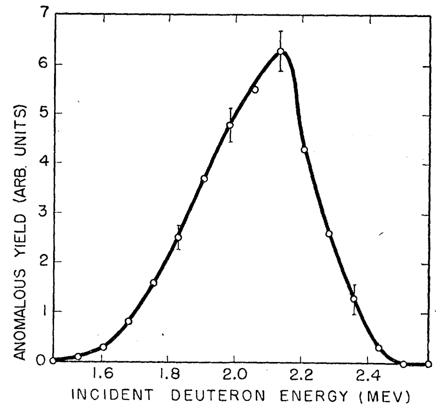

Fig. 2. Resonance in $C^{14}(d,p)C^{15}$. This curve was obtained by graphical subtraction of a postulated smooth excitation curve in this region.

of N^{16}. This calculation uses a reported[5] mass of N^{16} of 16.010740±0.0005 amu. As should be expected from the large excitation energy involved, the resonance is quite broad, having a width of nearly 400 kev.

The sharp rise in the experimental excitation curve starting at about 1.5 Mev suggests strongly that deuterons of higher angular momentum than $l=0$ play an important part in the reaction. For this reason it seemed interesting to compare the data with theoretical excitation functions calculated along standard lines by one of the authors (WWC). It was assumed that Coulomb barrier penetrability was the determining factor in the energy range considered. Of interest here is the fact that the shape of the excitation curve depends strongly on the spin of C^{15}. Comparison with experiment thus should give a determination of the spin.

On the basis of the shell model[6] the most probable spin and parity values for C^{15} are 1/2(+) and 5/2(+). In Table I are shown possible l values for the incoming deuterons and outgoing protons which obey the angular momentum and parity conservation laws.

In order to conserve parity the difference between l and l' must be an even integer [assuming 0(+) for the C^{14} ground state[7]]. The pairs of values in the table are all those possible such that $l+l'$ is 0 or 2. Possible pairs with higher l values, e.g., $l=1$, $l'=3$, contribute much less to the cross section because of their lower penetrability. The significant difference between the two possible spin values for C^{15} is that an $l=0$, $l'=0$ reaction which is most favored on a penetrability basis is possible for a spin of 1/2 but not for a spin of 5/2.

The cross section of the interaction is given by Bethe and Placzek's generalization[8] of the Breit-Wigner

[5] *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. 1.
[6] M. G. Mayer, Phys. Rev. **78**, 16 (1950).
[7] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1954).
[8] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).

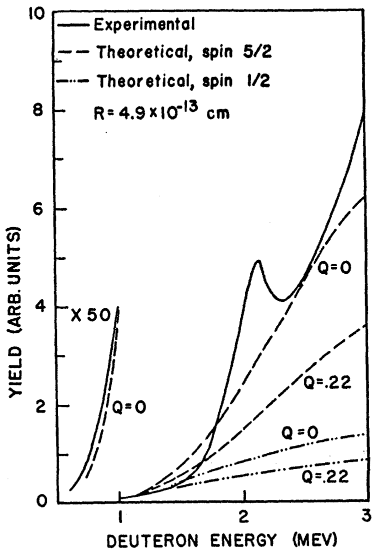

FIG. 3. Comparison of experimental and theoretical excitation curves for $C^{14}(d,p)C^{15}$ assuming C^{14} radius of 3.6×10^{-13} cm. Below 1 Mev all curves lie between the experimental curve and that shown for $Q=0[5/2(+)]$.

formula,[9]

$$\sigma=\frac{\pi\bar{\lambda}^2}{(2i+1)(2s+1)}\sum_{ljl'j'J}(2J+1)\times\left|\sum_r\frac{\mathcal{U}_{lj}{}^{rJ}\mathcal{U}_{l'j'}{}^{rJ}}{E_1-E_r+\frac{1}{2}(-1)^{\frac{1}{2}}\gamma_{rJ}}\right|^2,$$

where i is the spin of the initial nucleus and s is the spin of the incident particle. The quantities $\mathcal{U}_{lj}{}^{rJ}$ and $\mathcal{U}_{l'j'}{}^{rJ}$ are matrix elements of the interaction between the system "initial nucleus plus incident particle" and the compound nucleus in the first case, and between the compound nucleus and the system "final nucleus plus outgoing particle" in the second case. The letter r refers to all quantum numbers of the compound nucleus except its total angular momentum J. E_r is the energy of the state r, and E_1 is the total energy of the system initial nucleus plus incident particle. The quantum numbers of orbital and total angular momentum are l,j, respectively, for the incident particle and l',j' for the outgoing particle. The half-width of the level r,J is

$$\gamma_{rJ}=\sum_{q'}\sum_{l'j'}\gamma_{l'j'}{}^{rJ},$$

where the sum over q' is over the states of the various particles which can be emitted by the compound nucleus and

$$\gamma_{l'j'}{}^{rJ}=(\mathcal{U}_{l'j'}{}^{rJ})^2.$$

Penetrabilities have been computed using the WKB method as outlined in Bethe's review article.[10] The penetrability may be expressed as $e^{-2C_l(E)}$, C_l being a function of the energy E in the center-of-mass system of particle and nucleus, and of l. The quantity e^{-C_l} appears as a factor in the wave function and hence in the matrix element $\mathcal{U}_{lj}$. If $\mathcal{W}_{lj}$ is defined by

$$\mathcal{U}_{lj}=e^{-C_l}\mathcal{W}_{lj},$$

the cross section may be written

$$\sigma=\frac{\pi\bar{\lambda}^2}{(2i+1)(2s+1)}\sum_{ljl'j'J}(2J+1)e^{-2C_l(E)}e^{-2C_{l'}(E')}\times\left|\sum_r\frac{\mathcal{W}_{lj}{}^{rJ}\mathcal{W}_{l'j'}{}^{rJ}}{E_1-E_r+(-1)^{\frac{1}{2}}\gamma_{rJ}}\right|^2,$$

where $C_l(E)$ refers to the incident particle of energy E and $C_{l'}(E')$ to the outgoing particle of energy E'. The factor in absolute brackets involves the "partial half-widths without penetrability." This has been assumed to be a slowly varying function of the energy and also of the quantum numbers $ljl'j'J$. Since $\bar{\lambda}^2$ is proportional to $1/E$, the energy dependence of the cross section becomes

$$\sigma=KE^{-1}\sum_{ljl'j'J}(2J+1)e^{-2C_l(E)}e^{-2C_{l'}(E')},$$

where K is essentially constant over the energy range considered

For the pairs of ll' values in Table I, the sum over $jj'J$ leads to the weighting factors for $e^{-2C_l(E)}e^{-2C_{l'}(E')}$ given in Table II.

Comparison of calculated curves with the experimental data is shown in Figs. 3 and 4. The assumptions made about the internal conversion probability do not, of course, apply to the part of the cross section arising from the resonance at 2.15 Mev. The theoretical curves are conceived to describe the part of the cross section not caused by this level. Theoretical curves are shown for both possible spin values of C^{15}, for possible Q values of the reaction between $Q=0$ and $Q=0.29$ Mev ($Q=E'-E$), and for two values of the nuclear radius R. The smaller of these values, 3.6×10^{-13} cm, is $(1.5\times10^{-13}\text{ cm})A^{\frac{1}{3}}$, where A is 14. The higher of the values, 4.9×10^{-13} cm, is this plus about half the deuteron radius. All curves are normalized at 1 Mev. The difference in shape between the curves for spin 1/2 and those for spin 5/2 is caused mainly by the contribution of the $l=0$, $l'=0$ term. This term is larger than the remaining ones but has a fairly flat energy dependence. When the spin 1/2 curve, dominated by this term, is normalized to fit the low-energy data, it falls well below the experimental points at high energies.

It is clear that the curves for an assumed 5/2(+) ground state fit the data much better than those for an assumed 1/2(+) ground state. The best fit is for a

[9] G. Breit and E. P. Wigner, Phys. Rev. **49**, 519 (1936).
[10] H. A. Bethe, Revs. Modern Phys. **9**, 69 (1937).

Q value between 0 and 0.29 Mev.[11] A probable spin value of 5/2(+) for C^{15} compares with the same spin value for the ground state of O^{17}, which also has nine neutrons and an even number of protons. It contrasts with the 1/2(+) ground state of F^{19} with nine protons and ten neutrons. In all three cases there is a single odd nucleon outside closed shells. Apparently there is some tendency here for high angular momentum neutron states to lie lower, relatively, than high angular momentum proton states.

A spin of 5/2(+) is also indicated by the decay scheme of C^{15}, as Inglis[7] has pointed out. There appear to be two β rays, one with maximum kinetic energy of about 8.8 Mev and the other with about 3.3 Mev. If there is a branching ratio of 1:1, the log ft values for these are 5.6 and 3.6, respectively. The transition to the lower state thus seems to be first forbidden and that to the higher state allowed. The ground state of N^{15} is 1/2(−) and the first excited state is a doublet at about 5.3 Mev, which is probably 5/2(+), 7/2(+). A spin of 5/2(+) agrees with a first forbidden transition to the ground state and an allowed transition to the first excited state. A 1/2(+) spin would not lead to an allowed transition to the first excited state. The energy of the observed γ rays, about 5.5 Mev,[3] is in good agreement with the energy level difference between ground and first excited states.

Note added in proof.—The assumption of compound nucleus formation rather than an Oppenheimer-Phillips process is suggested by the resonance at 2.15 Mev, but it is certainly possible that the part of the cross section treated here, i.e., excluding the resonance, might be largely due to stripping. The cross section for an Oppenheimer-Phillips process, however, rises less steeply as a function of energy than the compound nucleus cross section [H. A. Bethe, Phys. Rev. **53**, 39 (1938)], and would fit the experimental data less well in the spin 1/2 case than the compound nucleus cross section. A spin of 1/2 thus seems unlikely in the case of either mechanism. Consistency of a spin of 5/2 with a reaction taking place by compound nucleus formation is indicated by the similar situation in the 5.3-Mev excited state of N^{15} produced by $N^{14}(d,p)N^{15}$ where the reaction is dominated by compound nucleus formation [S. T. Butler, Proc. Roy. Soc. (London) **208A**, 559 (1951)]. In the nitrogen case there is thought to be an angular momentum transfer (Butler's l_n) of 2 or more; in the carbon case l_n would have to be at least 2. It seems probable that this would discriminate against stripping in the carbon case as it does in the nitrogen case, especially since the Coulomb barrier for compound nucleus formation is lower for carbon.

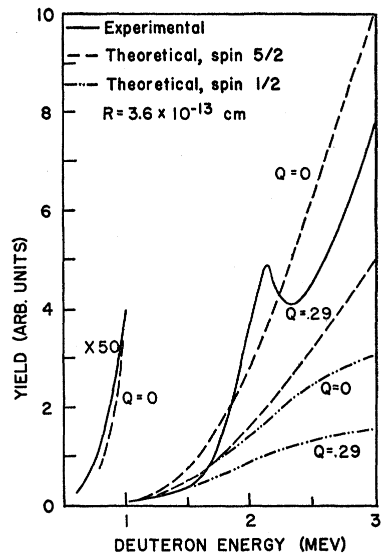

FIG. 4. Same as Fig. 3, except that the radius of C^{14} is assumed to be 4.9×10^{-13} cm.

TABLE II. Weighting factors.

Spin of 1/2			Spin of 5/2		
l	l'	Weight	l	l'	Weight
0	0	3	0	2	6
0	2	3	1	1	13
1	1	12	2	0	12
2	0	3			

IV. CONCLUSIONS

(1) The results of the present analysis of the excitation curve for $C^{14}(d,p)C^{15}$ lead to a Q value between 0 and 0.3 Mev; it appears probable that Q is 0.15±0.15 Mev, consistent with certain unpublished work[11] from this laboratory.

(2) On the basis of the above Q value and measured masses[5] of C^{15}, H^2, and H^1, the mass of C^{15} is 15.0141 ±0.00015 amu. This yields a $C^{15}-N^{15}$ mass difference of 8.6 Mev, which is consistent with the maximum energy of the observed β rays (8.8±0.5 Mev).

(3) The resonance in the $C^{14}(d,p)C^{15}$ excitation curve at a bombarding voltage of 2.15 Mev indicates a level of excitation in N^{15} at 12.8±0.5 Mev, with an experimentally observed width of about 400 kev.

(4) The most probable spin and parity value for the ground state of C^{15} is 5/2(+).

ACKNOWLEDGMENTS

The technical assistance of Joseph T. Peoples and the computational work of P. M. Clayton are gratefully acknowledged.

[11] The protons from the reaction have recently been observed by Dr. K. R. Spearman. The Q value which he obtains is 0.12 Mev, with a tentatively estimated error of about 0.05 Mev (to be published).