Triton Angular Distributions from 14.8-Mev Deuterons on C^{13}*

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An elemental carbon target enriched to 66% in C^{13} was bombarded with 14.8-Mev deuterons. Triton groups corresponding to the ground state, 4.43- and 7.65-Mev levels in C^{12} were magnetically analyzed and detected with photographic plates or a scintillation counter, at laboratory angles between 3 and 80 degrees. The angular distributions were found to be in good agreement with Butler pick-up theory, for $l=1$. The values of the cross sections at the peak of the angular distributions are 24.3, 9.6 and 0.36 mb/sterad, respectively. These values are accurate within ±25%. The relative reduced widths connecting C^{13} with the ground state, 4.43- and 7.65-Mev levels of C^{12} are 1:0.76:0.039. The results are discussed.

INTRODUCTION

A STUDY of the angular distributions of the reactions $C^{13}(d,t)C^{12}$ to the ground state (g.s.), 4.43- and 7.65-Mev levels was made using the 14.8-Mev deuteron beam from the University of Pittsburgh cyclotron. The reaction to the g.s. had been previously studied by Holmgren *et al.*[1] at low incident energies, 2.2 and 3.3 Mev.

Each of the three angular distributions considered in the present work indicates clearly a value $l=1$ for the orbital angular momentum of the transferred neutron. This is consistent with the known[2] spins and parities of 0^+, 2^+, and 0^+, respectively.

The angular distributions and the ratio of the reduced widths for the g.s. and 4.43-Mev levels of C^{12} are found to be in good agreement with the corresponding $C^{13}(p,d)C^{12}$ results.[3]

The significance of the reduced width for the 7.65-Mev level is discussed in connection with the structure of this low-lying 0^+ level. The small value, $\theta^2=0.0013$ suggests a small component of the s^4p^8 configuration.

EXPERIMENTAL PROCEDURE

The scattering apparatus used in this work has been described elsewhere.[4,5] Particles emerging from the target were magnetically analyzed and detected with a 30 mil thick CsI(Tl) crystal or with NTB Kodak nuclear emulsions 50 to 100μ thick. The scintillator was used when the triton tracks in the emulsion could not be counted due to the presence of large numbers of deuterons. This was the case for the 4.43-Mev level when detecting at angles higher than 30°, and for the 7.65-Mev level at all the angles measured. The angular acceptance of the detecting system was limited to 1°. The target used was a self-supporting foil of elemental carbon, enriched to 66% in C^{13}. It was made by cracking methyl iodide on a tantalum strip, from which a film 0.75 mg/cm² ±15% thick was peeled off.[6] The absolute values of the cross sections were found by comparison with the $C^{12}(d,p)C^{13}$ ground-state reaction[7] whose absolute cross section has been measured to within ±20%.[8] In addition to this uncertainly, the statistical error and the uncertainty in the determination of the enrichment ratio give a final error of approximately ±25%.

RESULTS

In Fig. 1 the observed angular distribution for the $C^{13}(d,t)C^{12}$ ground-state reaction is shown and compared with an $l=1$ Butler curve. The value of $r_0=4.6$ fermis is the same as is used to fit the $C^{12}(d,p)C^{13}$ ground-state reaction at $E_d=14.8$ Mev.[7]

Figure 2 shows the fit of an $r_0=5$ fermis, $l=1$ Butler

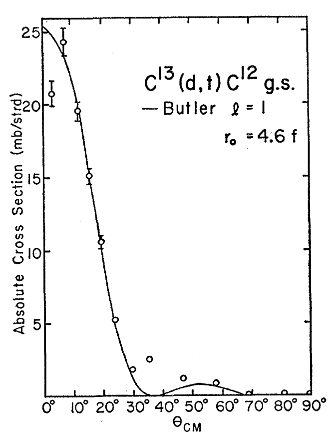

Fig. 1. Angular distribution of the $C^{13}(d,t)$-C^{12} ground-state reaction. The bars indicate the statistical errors; same for Figs. 2 and 3.

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[5] See also E. W. Hamburger, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

[6] We thank J. B. Meade for making the target. The procedure is described by G. C. Phillips and J. E. Richardson, Rev. Sci. Instr. **21**, 885 (1950).

[7] McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).

[8] E. W. Hamburger and S. Mayo (reference 5) remeasured the absolute cross section and found the value 15.5 mb/sterad ±20% at the peak of the angular distribution. J. N. McGruer *et al.* (reference 7) gave the value 26 mb/sterad ±50% at that angle.

curve with the experimental data of the $C^{13}(d,t)C^{12}$ 4.43-Mev reaction. The same radius can be used to fit the corresponding (p,d) reaction.[3]

In Fig. 3 the differential cross section for the $C^{13}(d,t)C^{12}$ 7.65-Mev level is shown to be in good agreement with an $l=1$ Butler curve using a cutoff radius of 6 fermis.

It is interesting to note that the cross sections fall by a factor of ten after the first maximum, and in particular that the transition to the 7.65-Mev level has an extremely low "background," ~0.03 mb/sterad. This has the consequence that a very clear stripping pattern can be seen although the transition is very weak.

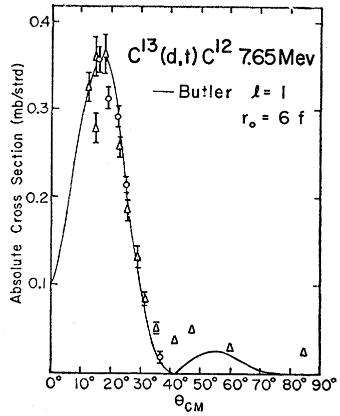

FIG. 3. Angular distribution of the $C^{13}(d,t)$-C^{12} 7.65-Mev level. △ points based on data taken by J. N. McGruer in an early stage of this work. ○ points measured recently. Both sets were taken with scintillator.

DISCUSSION

Angular distributions and reduced widths were calculated from a direct extension to (d,t) reactions of the usual Butler theory for (d,p) processes. The cross section (mb/sterad) is then given by:

$$\frac{d\sigma(\theta)}{d\Omega}=\frac{1}{8\pi}\frac{3}{2}\frac{\mu_t\mu_d}{\mu_n^2}\frac{k_t}{k_d}\frac{3\theta^2}{r_0}\times\left[P_t(\mathbf{k})\frac{r_0W_l[j_l(qr),h_l^{(1)}(iKr)]_{r=r_0}}{h_l^{(1)}(iKr_0)}\right]^2, \quad (1)$$

where the μ_i are the reduced masses of the systems: triton+nucleus A, deuteron+nucleus $A+1$, neutron +nucleus A; k_t and k_d the triton and deuteron wave vectors; θ^2 is the reduced width in units of

$$\frac{3}{2}\frac{\hbar^2}{\mu_n r_0^2}(T_0\tfrac{1}{2}M_{T_0}\tfrac{1}{2}|T_0\tfrac{1}{2}T_1M_{T_1})^2,$$

i. e., the Wigner limit times the square of the Clebsch-Gordan coefficient for the isotopic spin coupling factor; r_0 is the cutoff radius; W_l is the wronskian for the spherical Bessel and Hankel functions $j_l(qr)$ and $h_l^{(1)}(iKr)$ where $\mathbf{q}$ is the momentum transferred $\mathbf{q}=\mathbf{k}_d-[A/(A+1)]\mathbf{k}_t$ and $\mathbf{K}$ is the wave vector of the neutron with respect to the core;

$$P_t(\mathbf{k})=\int_0^\infty e^{i\mathbf{k}\cdot\mathbf{r}}\phi_t(\boldsymbol{\xi},\mathbf{r})\phi_d(\boldsymbol{\xi})d\mathbf{r}d\boldsymbol{\xi},$$

with $\mathbf{k}=\mathbf{k}_d-\frac{2}{3}\mathbf{k}_t$, $\boldsymbol{\xi}=\mathbf{r}_{p1}-\mathbf{r}_{n1}$ and $\mathbf{r}=\mathbf{r}_{n2}-\boldsymbol{\xi}/2$.

The triton wave function was taken to be:

$$\phi_t=\frac{B}{(4\pi)^{\frac{1}{2}}}\frac{e^{-\gamma r}}{r}\phi_d(\boldsymbol{\xi}).$$

B is the normalizing constant, $\gamma^2=\frac{4}{3}(m/\hbar^2)\epsilon$, m=nucleon mass and ϵ the binding energy of the neutron in the triton, 6.2 Mev.

Using Eq. (1) the fit with experiment gives the quantity $B^2\theta^2$. Therefore, once B^2 is determined, (d,p) and (d,t) reactions involving the same transition would give the same value for the reduced width. Evidence that this is true has also been found comparing several other such cases.[9] In the present experiment the ratio $\theta^2(4.43)/\theta^2$ (g.s.) is 0.76 in satisfactory agreement with the value 0.92 extracted from $C^{13}(p,d)C^{12}$ (see Table I).

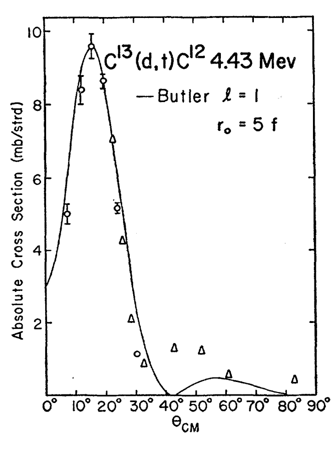

FIG. 2. Angular distribution of the $C^{13}(d,t)$-C^{12} 4.43-Mev level. ○ points measured with nuclear emulsions; △ points measured with scintillator.

TABLE I. Reduced widths for transitions between C^{13} g.s. and the g.s., 4.43- and 7.65-Mev levels of C^{12}.

Reaction	E_L[d] (Mev)	E_i (Mev)	Q (Mev)	l	r_0 (fermis)	θ^2	Relative θ^2
$C^{12}(d,p)C^{13}$ [a]	0	14.8	2.723	1	4.6	0.033	1
$C^{13}(p,d)C^{12}$ [b]	0	17	−2.723	1	4.6		1
	4.43			1	5		0.92
$C^{13}(d,t)C^{12}$ [c]	0	3.3	1.309	1	5.6	0.034	
$C^{13}(d,t)C^{12}$	0	14.8	1.309	1	4.6		1
	4.43			1	5	0.025	0.76
	7.65			1	6	0.0013	0.039

[a] From reference 7 and reference 8.
[b] From reference 3.
[c] From reference 1.
[d] E_L is the excitation energy in the final nucleus; E_i is the energy of the incident particles in the laboratory system; Q of the reaction; l is the angular momentum transferred; r_0 is the Butler radius in units of 10^{-13} cm; θ^2 is the dimensionless reduced width; the last column gives the ratios of the reduced width for the levels to the corresponding ground state reduced width.

[9] A study of several (d,t) reactions compared with (d,p) has been made by A. I. Hamburger and is to be published.

The value of $B^2\,\theta^2$ for the transition to the g.s. is 0.031×10^{13} cm^{-1}. Taking $\theta^2=0.033$, as determined in the $C^{12}(d,p)C^{13}$ reaction, B^2 is found to be 0.94×10^{13} cm^{-1}. This value was used to calculate the reduced widths of the higher levels in C^{12}.

Table I summarizes the values obtained for θ^2 for the various reactions. The reduced width of $C^{13}(d,t)C^{12}$ g.s. with deuterons of 3.3 Mev, from the data of Holmgren *et al.*,[1] was also calculated. The value of $B^2\,\theta^2$ found is in very good agreement with that determined in the present experiment; this is surprising in view of the low deuteron energy.

The reduced width for the 7.65-Mev level is found to be $\theta^2=0.0013$. This is a very small value for a transition involving an $l=1$ particle, for the $1p$ single particle reduced width is $\theta_{01}{}^2(1p)\sim 0.06$.[10] As French points out,[11] the small θ^2 is either the result of an "accidental" cancellation among various amplitudes which is not describable by a standard selection rule or it shows the effectiveness of such a rule. It is not possible to state with certainty which is operating. However, Inglis[12] and also Kurath[13] have shown that using normal interactions with an intermediate coupling model an excited 0^+ level from the s^4p^8 configuration would be much higher in excitation.[14] Therefore, one tends to accept that there is a configuration selection rule, so that the small θ^2 indicates that the level has a small component of s^4p^8 configuration.

Thus, the 7.65-Mev level would belong predominantly to other configurations which cannot be reached from the C^{13} g.s., an s^4p^9 state. The probable configurations to contribute would be those with one particle doubly excited or two particles singly excited, namely,

$$(1s)^4(1p)^7(2p)+(1s)^3(1p)^8(2s)+(1s)^4(1p)^6[(2s)^2+(2d)^2+2s2d]$$

This is as much as can be said from the results of the present experiment. However it is interesting to speculate about other experiments which could give some further information.

The $(1s)^4(1p)^7(2p)$ component, together with the s^4p^8, can be measured experimentally by means of the $B^{11}(d,n)C^{12}$ reaction [or (He^3,d)]. Unfortunately, a complete study of this reaction is not available. A tentative calculation based on the work of Maslin, Calvert, and Jaffe[15] gives an upper-limit $\theta_{l=1}{}^2<0.01$. However, it is not clear if this is large or small, in part because the $(2p)$ single particle reduced width, $\theta_{01}{}^2(2p)$, has not been determined.

Therefore, the $O^{16}(d,p)O^{17}$ reaction to the negative parity levels of O^{17} would also be of interest for it would determine the value of $\theta_{01}{}^2(2p)$. In addition, this experiment would locate the $2p$ single particle level; knowing the position of that level, it should be possible to calculate if the 7.65-Mev state in C^{12} has a major $2p$ component.[16]

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[14] Sydney Meshkov (private communication) has done some calculations showing that with a different central interaction one can produce an s^4p^8 0^+ level at 7.65 Mev which at the same time has a small reduced width. However, the interaction used would not give satisfactory treatment for the $T=1$ levels.

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[16] Some preliminary calculations have been done by S. Meshkov (private communication).