There is little to choose between a $7/2^-$ and a $9/2^-$ spin assignment for the proposed 0.878-MeV state of Rb^{85} based upon the data available. The branching ratios calculated in a similar way for these two spin choices, considered with tabulated experimental deviations of these branching ratios from the predictions of Weisskopf formula,[15] are consistent with the experimental data for both spin choices.

The above discussion is consistent with the failure to find any appreciable transitions from the $1/2^-$ state of Sr^{85m} to the 0.878-MeV state of Rb^{85}. It is also consistent with the decay scheme of Kr^{85} and[4] Kr^{85m} which have not shown a 0.878-MeV level in Rb^{85}. This 0.878-MeV level is not accessible to the ground state of Kr^{85} and Kr^{85m} has a spin of $1/2^-$. A transition by beta decay between a $1/2^-$ and $7/2^-$ or $9/2^-$ state would be very highly forbidden.

The positrons found in the coincidence experiment are attributed to Rb^{84} or another positron-emitting impurity in the Sr^{85} sample. No transitions directly to the ground state have been found in the decay of Sr^{85}. Such a transition would be a first-forbidden unique transition. All tabulated first forbidden unique transitions have log ft values $\geqslant 8.16$ for odd-A nuclei[16] Assigning, for the sake of argument, a log ft value of 8.16 for the transition to the ground state of Rb^{85} gives a ratio (ground-state decay)/(decay to 0.514-MeV state) $<3\times10^{-2}$. The ratio of β^+/K for this transition to the ground state would be $\lesssim 2\times10^{-5}$.[17] Thus, the branching ratio for the decay of Sr^{85} by positron emission relative to electron capture (or relative to the observable 0.514-MeV gamma ray) is very likely to be $<6\times10^{-7}$. It is therefore unlikely that the positron activity seen is due to Sr^{85}.

ACKNOWLEDGMENTS

I wish to give acknowledgment to Dr. W. W. Pratt of The Pennsylvania State University for his suggestions and discussions which were an immeasurable aid in carrying out this investigation. I wish also to give acknowledgment to Douglas S. Vonada of The Pennsylvania State University Research Reactor staff for his innovations, aid, and suggestions concerning the electronic apparatus used in this investigation.

[15] W. W. Pratt, Nuclear Phys. **28**, 598 (1961).

[16] C. S. Wu, in *Nuclear Spectroscopy*, edited by Fay Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part A, pp. 139–169.

[17] Based on extrapolating curves of P. F. Zweifel, in *Proceedings of The Rehovoth Conference on Nuclear Structure, Rehovoth, Israel, 1957*, (Interscience Publishers, Inc., New York, 1958), pp. 300–315.

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Endothermic Deuteron Stripping Reactions. III. The $C^{14}(d,p\gamma)C^{15}$ and $Li^7(d,p\gamma)Li^8$ Reactions*

L. F. CHASE, JR., R. G. JOHNSON, F. J. VAUGHN, AND E. K. WARBURTON†
Lockheed Missiles and Space Research Laboratory, Palo Alto, California

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The cross section of the $C^{14}(d,p)C^{15*}$ reaction ($Q=-1.76$ MeV) to the first excited state of C^{15} at 0.75 MeV was measured for deuteron energies between 2.7 and 3.4 MeV. The cross section was obtained from the yield of the γ ray to the C^{15} ground state. The energy of this γ ray was measured to be 0.750 ± 0.007 MeV. The γ-ray angular distribution relative to the deuteron beam was measured at five deuteron energies between 2.9 and 3.4 MeV. The presence of a $P_4(\cos\theta)$ term in the distributions together with previous work establishes the C^{15} 0.75-MeV level as $5/2^+$. The measured angular distributions were found to be in agreement with predictions based on stripping theory. The cross section for the $Li^7(d,p)Li^{8*}$ reaction ($Q=-1.17$ MeV) to the first excited state of Li^8 at 0.98 MeV was measured for deuteron energies between 1.9 and 3.3 MeV. The cross section was obtained from the yield of the γ ray to the Li^8 ground state. The γ-ray energy was measured to be 0.980 ± 0.010 MeV. The anisotropy of this γ ray was measured at 23 deuteron energies between 1.9 and 3.3 MeV. These results were also consistent with the predictions of stripping theory if assignments of 1^+ for the Li^8 0.98-MeV level and $M1$ for the 0.98-MeV γ ray are assumed.

I. INTRODUCTION

In the first paper[1] of this series it was argued that the stripping mechanism should contribute all or nearly all of the cross section for many endothermic (d,p) or (d,n) reactions near threshold. Several methods of investigating the relative contribution of the stripping and compound nucleus mechanisms to the cross section near threshold in endothermic (d,p) or (d,n) reactions were discussed. In particular, the angular distribution of the γ rays relative to the deuteron beam (intermediate particle unobserved) in a $(d,p\gamma)$ or $(d,n\gamma)$ reaction was considered in some detail.

In the second paper[2] of this series the method of

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† Summer Visitor, 1960. Permanent Address: Brookhaven National Laboratory, Upton, New York.

[1] E. K. Warburton and L. F. Chase, Jr., Phys. Rev. **120**, 2095 (1960); hereafter referred to as I.

[2] L. F. Chase, Jr., R. G. Johnson, and E. K. Warburton, Phys. Rev. **120**, 2103 (1960); hereafter referred to as II.

analyzing $(d,p\gamma)$ angular distributions developed in I was applied to the $C^{12}(d,p_3\gamma)C^{13*}$ reaction and it was found that the anisotropy of the C^{13} 3.85 → 3.68-MeV transition relative to the deuteron beam was consistent with the predictions of plane-wave stripping for deuteron energies below 2.4 MeV (the threshold for this reaction is 1.33 MeV). As was pointed out in II, the agreement with plane-wave stripping theory in this case does not necessarily rule out compound nucleus formation since it is possible to reproduce the observed anisotropy assuming the latter reaction mechanism. It is true that the simplest and most likely explanation of the $C^{12}(d,p_3\gamma)C^{13*}$ results is that the reaction proceeds by the stripping mechanism in the energy region near threshold. However, to strengthen the argument that the stripping mechanism predominates near (d,n) or (d,p) thresholds, it is desirable to study as many cases as possible. Then, if agreement with the predictions of the stripping theory is obtained in all cases studied, the probability of chance agreement with other reaction mechanisms is considerably lessened.

In this paper measurements of the γ-ray anisotropy relative to the deuteron beam in the $C^{14}(d,p\gamma)C^{15}$ (0.75-MeV level) and $Li^7(d,p\gamma)Li^8$ (0.98-MeV level) reactions are reported.[3] The Q values of these reactions are -1.76 and -1.17 MeV, respectively, with thresholds of 2.0 and 1.5 MeV. Thus, both reactions could be investigated in the energy region of interest—threshold to about $E_d=-2Q$ (see I)—with the 3.5-MeV Lockheed Van de Graaff which was available for this work. These reactions were chosen for the above reason and for the following additional reasons: firstly, although the spins of the C^{14} 0.75-MeV level and Li^8 0.98-MeV level were not established at the onset of this work, there was strong theoretical evidence that they were $\frac{5}{2}^+$ and 1^+, respectively. For these spin assignments the C^{15} 0.75-MeV level has approximately a single-particle d-wave reduced width while the Li^8 0.98-MeV level has about one-half a single-particle p-wave reduced width[4] and therefore both reactions have intrinsically large stripping cross sections. Secondly, the zero spin of the C^{14} ground state simplifies the analysis of the $C^{14}(d,p\gamma)C^{15}$ results, and, although the analysis of the $Li^7(d,p)Li^8$ reaction is in principle complicated by the possibility of two channel spins ($\mathbf{s}=\frac{1}{2}+\mathbf{J}_0=\frac{1}{2}+\frac{3}{2}=1$ or 2) contributing to the reaction, there exist reliable theoretical predictions[5] with which the experimental results from the $Li^7(d,p\gamma)Li^8$ reaction can be compared. Thirdly, the C^{15} 0.75-MeV level and the Li^8 0.98-MeV level are the only known excited states below the neutron binding energy in these nuclei. Thus, there is no complication due to γ-ray cascades from higher excited states.

The expected angular distribution of the γ rays following an endothermic deuteron stripping reaction can be written in the form (see I)

$$W(\theta)=\sum_{\nu=0}^{\nu_{max}} a_\nu Q_\nu P_\nu(\cos\theta), \tag{1}$$

where θ is the angle between the directions defined by the deuteron beam and the outgoing γ rays. The coefficients a_ν are those for a resonant (nucleon, γ) capture reaction given, for instance, by Devons and Goldfarb.[6] The coefficients Q_ν are attentuation factors which depend on the deuteron energy and arise from consideration of the finite solid angle into which the residual nucleus recoils. Assuming plane-wave stripping theory and an isotropic distribution of the outgoing nucleons in the center-of-mass system, Q_2 and Q_4 can be written as (see I)

$$Q_2=1-\tfrac{3}{8}(1+\alpha^2)+\frac{3}{16\alpha}(1-\alpha^2)^2\ln\frac{1+\alpha}{1-\alpha},$$
$$Q_4=7/12+(5/12)(1-7\alpha^2)Q_2, \tag{2}$$

where α is defined as the ratio of the wave number of the outgoing nucleons to the wave number of the incoming deuterons in the center-of-mass system. The effects of initial and final state interactions on the Q_ν factors are discussed in I.

II. EXPERIMENTAL PROCEDURE

A. The $C^{14}(d,p\gamma)C^{15}$ (0.75-MeV level) Reaction

The C^{14} target was prepared by electro-depositing acetylene made from $BaCO_4$ enriched to 80% in C^{14} onto a 2-mg/cm² gold backing.[7] The C^{14} target thickness was obtained from a measurement of the widths of the 1162-keV and 1314-keV resonances in the $C^{14}(p,n)N^{14}$ reaction.[8] The neutron yield at 90° as a function of the proton energy was measured using a standard long counter.[9] From an analysis of these data a target thickness of 0.6 ± 0.1 mg/cm² was obtained. This thickness amounts to an energy loss of 110 keV for 3-MeV deuterons. In addition, the amounts of C^{14}, C^{12}, and O^{16} in the target were determined by experiments performed using the Princeton FM cyclotron.[10,11] The results were 0.28 ± 0.07 mg/cm² of C^{14}, 0.25 ± 0.02 mg/cm² of C^{12}, and 0.13 ± 0.02 mg/cm² of O^{16}.

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[3] These results were previously given in abstract form: L. F. Chase, Jr., R. G. Johnson, F. J. Vaughn, and E. K. Warburton, Bull. Am. Phys. Soc. **6**, 25 (1961).

[4] M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).

[5] J. B. French and A. Fujii, Phys. Rev. **105**, 652 (1957); J. B. French in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, pp. 895–931. See also reference 4.

[6] S. Devons and L. J. B. Goldfarb, *Handbuch der Physik* (Springer-Verlag, Berlin, 1957), Vol. **42**, p. 362.

[7] The target was prepared by W. E. Moore and J. N. McGruer. We would like to thank Dr. Moore for sending the target to us.

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

[9] *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960), pp. 361ff.

[10] J. Legg (to be published).

[11] F. P. Brady and E. K. Warburton (to be published).

The γ rays were detected in a 1-in. diam by 1-in. long NaI(Tl) crystal which was placed in a lead shield and positioned on an angular correlation table at a distance of 8 in. from the target. The target was mounted on a 0.005-in. tantalum backing and placed in a thin-walled cylindrical brass target chamber. Radioactive sources were used to check the alignment of the angular correlation table. The angular distribution data were corrected for absorption in the tanatlum backing. The correction due to the finite solid angle subtended by the NaI crystal was negligible for the geometry used.

The absolute counting efficiency for the NaI(Tl) detector was obtained using calibrated radioactive sources of Cs^{137} (0.662-MeV γ ray) and Mn^{54} (0.835-MeV γ ray), the intensities of which were known to better than 5%. The calibrated sources were placed at the target position in the experimental geometry which was used, and the counts in the total absorption peak were obtained in a manner identical to the way in which the actual data were analyzed (see the area included by the dashed curve in Fig. 1). The total absorption peak efficiencies thus obtained were plotted against γ-ray energy on log-log graph paper, and the efficiency for the 750-keV γ ray was interpolated.

Pulses from the γ-ray detector were sent through an amplifier and into a 400-channel analyzer. A pulse-height spectrum obtained from the $C^{14}(d,p\gamma)C^{15}$ reaction at a deuteron energy of 3.35 MeV and at an angle of 148 deg to the deuteron beam is shown in Fig. 1. The photopeak due to the C^{15} $0.75 \rightarrow 0$-MeV transition is labeled. The photopeak of the 0.871-MeV γ ray from the $O^{16}(d,p\gamma)O^{17}$ reaction is barely discernable at about channel 55 in Fig. 1. At a deuteron energy of 2.9 MeV, the lowest energy at which an angular distribution was obtained, this γ ray was comparable in intensity to the 0.75-MeV γ ray. However, the two γ-ray lines were resolved sufficiently so that only a slight error was added to the determination of the 0.75-MeV γ-ray intensity by the presence of the 0.871-MeV γ ray. Extractions of the intensity of the 0.75-MeV γ-ray line from the spectra were aided by comparison with spectra taken below the apparent threhsold for production of the 0.75-MeV γ ray and by comparison with spectral shapes from radioactive sources emitting γ rays of comparable energies.

The energy of the 0.75-MeV γ ray was measured relative to the peaks in the same spectrum due to annihilations and to the O^{17} 0.871-MeV γ ray. The energy of the latter is known to 3 keV.[8] The result was 0.750 ± 0.007 MeV.

The assignment of the 0.75-MeV γ ray, which had not been reported previously, to the C^{15} $0.75 \rightarrow 0$ transition was made primarily for the following reasons: Firstly, the measured value of the γ-ray energy agrees well with the excitation energy, 0.745 ± 0.020 MeV,[12] of the first excited state of C^{15}, while no γ rays of this energy are expected from deuteron reactions on C^{12} or any of its likely contaminants. Furthermore, a natural carbon target, prepared[7] in the same manner as the enriched C^{14} target, was bombarded with deuterons and the resulting γ-ray spectrum showed no evidence of a 0.75-MeV γ ray, although in all other respects the γ-ray spectrum was similar to that from the enriched target.

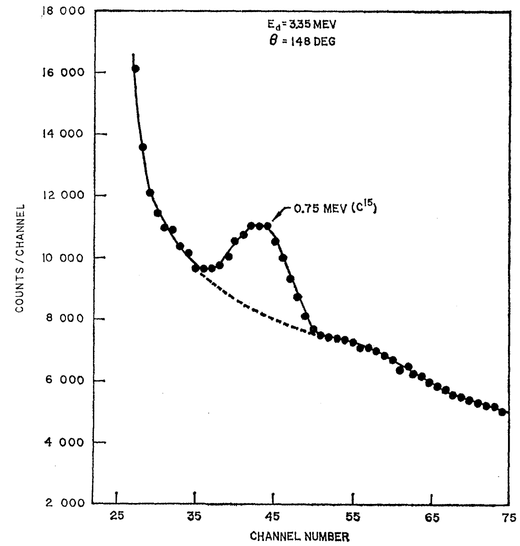

FIG. 1. A pulse-height spectrum showing the total absorption peak of the 0.750-MeV γ ray from the $C^{14}(d,p\gamma)C^{15}$ reaction at a deuteron energy of 3.35 MeV. The spectrum was obtained with a 1-in. diam by 1-in. long NaI(Tl) crystal at 148° to the deuteron beam.

B. The $Li^7(d,p\gamma)Li^8$ (0.98-MeV level) Reaction

The lithium target was prepared by evaporation of natural (92.5% Li^7) lithium metal onto a 0.005-in. tanalum backing. A specially constructed evaporation chamber was mounted on top of the target chamber, thus allowing the lithium target to be dropped into position without exposing it to air. The target thickness was obtained from a long counter measurement of the yield curve for neutrons at the $Li^7(p,n)Be^7$ threshold. The result was a thickness of 1.1 ± 0.3 mg/cm^2, corresponding to an energy loss of 172 keV for 3-MeV deuterons.

The experimental arrangement used in this work was similar to that used in the $C^{14}(d,p\gamma)C^{15}$ experiment except that the smaller NaI(Tl) crystal was replaced by two 2-in. diam by 2-in.-long NaI(Tl) crystals in order to increase the γ-ray detection efficiency and to record spectra at two angles simultaneously. A pulse-height spectrum obtained at a deuteron energy of 2.89 MeV and at an angle of 60 deg to the beam is shown in Fig. 2. The Li^8 0.98-MeV γ ray is labeled.

The absolute counting efficiencies for the 2-in. diam by 2-in. long NaI(Tl) detectors were determined in a manner similar to that used for the 1-in. diam by 1-in.

[12] W. E. Moore, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

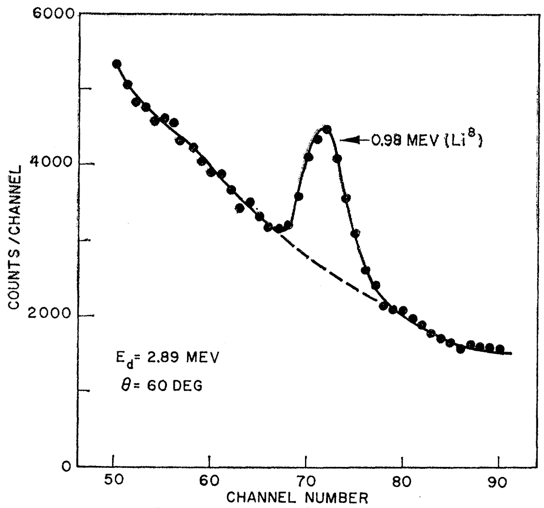

FIG. 2. A pulse-height spectrum showing the total absorption peak of the 0.98-MeV γ ray from the $Li^7(d,p\gamma)Li^8$ reaction at a deuteron energy of 2.89 MeV. The spectrum was obtained with a 2-in. diam by 2-in. long NaI(Tl) crystal at 60° to the deuteron beam.

long NaI(Tl) detector (see preceding section). Here, however, calibrated sources of Mn^{54} (0.835-MeV γ ray) and Zn^{65} (1.114-MeV γ ray) were used, and the total absorption peak efficiency for the 0.98-MeV γ ray was obtained again by interpolation.

The energy of the γ ray produced in the $Li^7(d,p\gamma)Li^8$ reaction was measured to be 0.980±0.010 MeV, using as standards the γ-ray lines at 0.511 MeV (Zn^{65}), 1.114 MeV (Zn^{65}), and 0.835 MeV (Mn^{54}). This value is in agreement with the excitation energy[8] of 0.975 ±0.012 MeV reported for this first excited state of Li^8. Assignment of the 0.98-MeV γ ray, which had not been previously reported, to the $Li^7(d,p\gamma)Li^8$ (0.98-MeV level) reaction was made on the basis of this energy agreement and because no γ ray of this energy is expected from any likely comtaminant.

III. RESULTS AND DISCUSSION

A. The $C^{14}(d,p\gamma)C^{15}$ (0.75 MeV level) Reaction

Angular distributions of the 0.75-MeV γ ray which were measured at deuteron energies (energy at mid-thickness of the target, $\bar{E}_d$) of 2.91, 3.09, 3.25, 3.32, and 3.39 MeV are shown in Fig. 3. The angular distributions were all fitted to a Legendre polynomial expansion by the method of least squares, and, in general, it was found that a term in $P_4(\cos\theta)$ was necessary to fit them adequately. The need for a term in $P_4(\cos\theta)$ is perhaps best illustrated by the average angular distribution shown in Fig. 4. This distribution was obtained by weighting the distributions obtained at the five deuteron energies inversely as the square of their errors. The result corresponds to an average deuteron energy $\bar{E}_d$, of 3.2 MeV. The presence of a $P_4(\cos\theta)$ term in the angular distribution fixes the spin of the C^{15} 0.75-MeV level as $\geqslant\frac{5}{2}$ regardless of the reaction mechanism.

Moore[12] found that the angular distribution of the $C^{14}(d,p\gamma)C^{15}$ (0.75-MeV level) could be fitted by the plane-wave stripping theory at E_d=14.9 MeV with l_n=1, 2, or 3. The assignment of l_n=2 is preferred because the values of the stripping radius r_0 needed to fit the observed angular distribution are outside of the expected range for l_n=1 or 3.

The cross section observed by Moore[12] also favors l_n=2. The l_n=3 reduced width calculated[13] from Moore's cross section is about four times the single-particle value given by Macfarlane and French.[4] The C^{14} ground state is well known to be predominantly a p-shell level and the upper limit to the reduced width for adding an inequivalent nucleon to a given state is the single-particle reduced width.[4] Thus, an assignment of l_n=3 (or higher l_n values) is in disagreement with stripping theory. An l_n=1 angular distribution would correspond[12] to a $s^4p^{10}2p$ state of C^{15}, since the neutron $1p$ shell is already filled at C^{14} so a p neutron could only be added in the $2p$ shell. Again the single-particle reduced width for $2p$-nucleons is much smaller than the observed reduced width for the $C^{14}(d,p)C^{15}$ (0.75-MeV level) reaction so that the stripping results rule against l_n=1. In any case, the present results do not allow the $\frac{1}{2}^-$ or $\frac{3}{2}^-$ assignment corresponding to l_n=1 and also

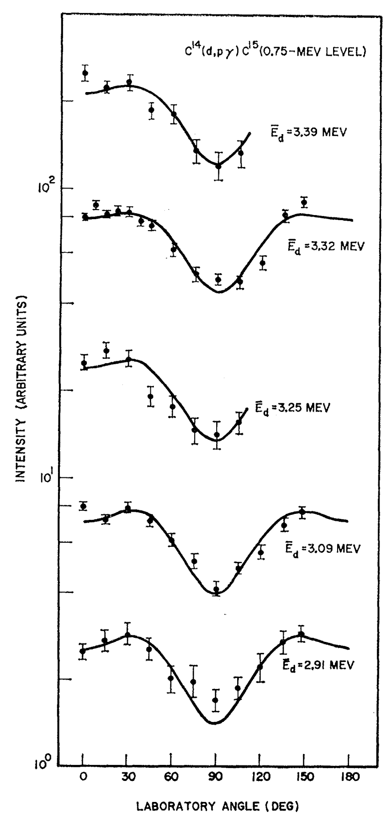

FIG. 3. Angular distributions for the C^{15} 0.75-MeV γ ray. The solid curves are the predictions of plane-wave stripping theory for a $\frac{5}{2}^+\rightarrow\frac{1}{2}^+$ γ-ray transition (see text).

[13] J. Lowe and C. L. McClelland (private communication).

rule out the possibility of $\frac{3}{2}^+$ which is allowed by $l_n=2$. Thus, the $C^{14}(d,p)C^{15}$ results of Moore together with the present measurements of the $C^{14}(d,p\gamma)C^{15}$ reaction fix the spin and parity of the C^{15} 0.75-MeV level as $\frac{5}{2}^+$ and require that it be formed in the stripping reaction by the capture of $l_n=2$ neutrons with approximately the single-particle reduced width.

The C^{15} ground state has been shown to have positive-parity by Alburger, Gallmann, and Wilkinson,[14] who studied the beta decay of C^{15}. The stripping angular distribution obtained by Moore[12] for the $C^{14}(d,p)C^{15}$ ground-state reaction allows $l_n=0$ or 1, with $l_n=0$ preferred because r_0 is rather large for $l_n=1$. Thus, since $l_n=0$ corresponds to $J^\pi=\frac{1}{2}^+$ while $l_n=1$ corresponds to $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$, the C^{15} ground state is fixed as $J^\pi=\frac{1}{2}^+$. This assignment is reinforced by the cross section obtained by Moore which rules against $l_n=1$ for the same reason, and to the same extent, as in the case of the $C^{14}(d,p)C^{15}$ (0.75-MeV level) reaction. The assignment of $\frac{1}{2}^+$ to the C^{15} ground state is also unambiguously given[15] by observation of the $C^{14}(d,p)C^{15}$ angluar distribution at a deuteron energy of 3.0 MeV, at which energy the $l_n=0$ curve is easily distinguished from higher l_n values.

If the cross section near threshold is due to the stripping mechanism in the $C^{14}(d,p\gamma)C^{15}$ (0.75-MeV level) reaction, the expected γ-ray angular distribution function for this $\frac{5}{2}^+\rightarrow\frac{1}{2}^+$ $E2$ transition is

$$W(\theta,E_d)=1+0.5714Q_2(E_d)P_2(\cos\theta)-0.5714Q_4(E_d)P_4(\cos\theta), \quad (3)$$

where Q_2 and Q_4 are attenuation coefficients which depend on the deuteron energy. They are limited by the

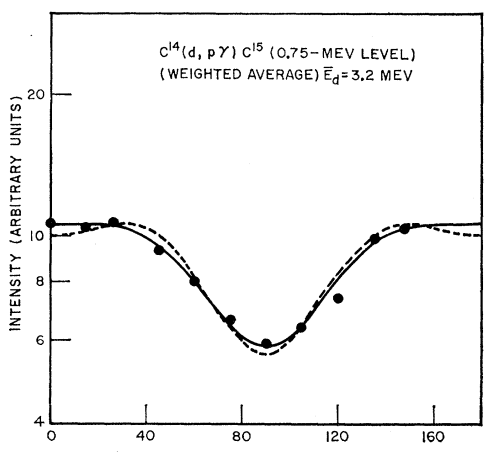

FIG. 4. Angular distribution of the C^{15} 0.75-MeV γ-ray for an average deuteron energy of 3.2 MeV. The solid curve is a least squares fit to the experimental points, $W(\theta,E_d)$. The dashed curve is the prediction of plane-wave stripping theory (reference 1) for a $\frac{5}{2}^+\rightarrow\frac{1}{2}^+$ γ-ray transition (see text).

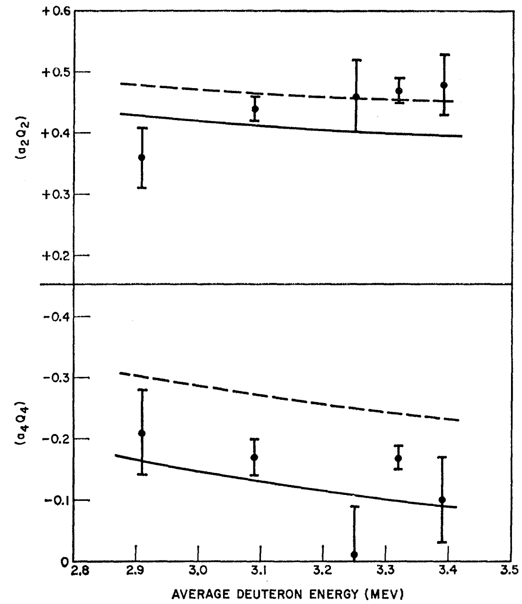

FIG. 5. The (a_2Q_2) and (a_4Q_4) coefficients as a function of deuteron energy obtained from the angular distributions of the 0.750-MeV γ ray from the $C^{14}(d,p\gamma)C^{15}$ reaction. The curves are the predictions of plane-wave stripping theory for an isotropic distribution of the outgoing protons (dashed curves) and for the angular distribution of the outgoing protons which yields the smallest possible values of Q_2 and Q_4 (solid curves).

requirement that $0<Q_\nu<1$ for the energies investigated, with the further condition that $Q\rightarrow1$ as $E_d\rightarrow$ threshold. The distributions predicted, under the simplifying assumptions of plane-wave stripping and an isotropic distribution of the outgoing protons in the center-of-mass system, are shown by the solid curves in Fig. 3 for the five angular distributions measured. They are arbitrarily normalized in intensity to fit the data points. For $E_d=3.2$ MeV, again with the simplifying assumptions, the distribution function is calculated from Eqs. (2) and (3) to be,

$$W_{\rm th}(\theta,3.2)=1+0.459P_2(\cos\theta)-0.250P_4(\cos\theta). \quad (4)$$

The coefficients in this distribution can be compared with the coefficients obtained by the method of least squares for the "averaged" distribution at $\bar{E}_d=3.2$ MeV, which is

$$W_{\rm exp}(\theta,3.2)=1+(0.46\pm0.03)P_2(\cos\theta)-(0.15\pm0.03)P_4(\cos\theta). \quad (5)$$

Plots of $W_{\rm th}$ and $W_{\rm exp}$ are given by the dashed and solid curves, respectively, in Fig. 4.

The "averaged" (a_2Q_2) coefficient is in excellent agreement with the simplified theory while the (a_4Q_4) coefficient shows more attenuation than the simplified theory predicts. The (a_2Q_2) and (a_4Q_4) coefficients which were obtained from the least-square analysis of the five angular distributions are shown in Fig. 5 as a function of deuteron energy. Also shown are the predictions (dashed

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[14] D. E. Alburger, A. Gallmann, and D. H. Wilkinson, Phys. Rev. **116**, 939 (1959).

[15] D. H. Wilkinson, Brookhaven National Laboratory Report BNL-5013, 1960 (unpublished).

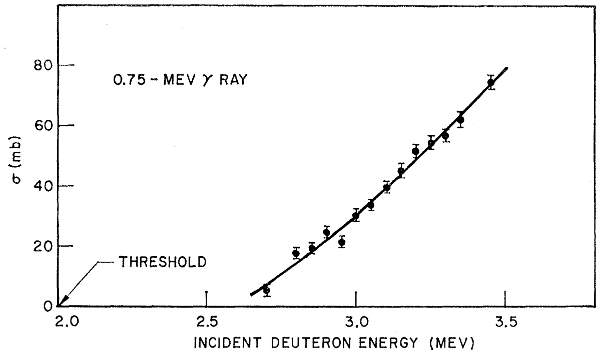

FIG. 6. The total cross section for the $C^{14}(d,p)C^{15}$ (0.75-MeV level) reaction as a function of deuteron energy. The total cross section scale (ordinate), which has an uncertainty of 30%, was obtained from the yield and angular distribution of the 0.75-MeV γ rays (see text).

curves) of Eq. (3), with the Q_2 and Q_4 given by Eq. (2), and the smallest possible values of (a_2Q_2) and (a_4Q_4) allowed by plane-wave stripping theory (solid curves). These latter correspond to $Q_\nu = P_\nu[(1-\alpha^2)^{\frac{1}{2}}]$, i.e., a delta-function angular distribution of the outgoing protons such that the recoiling nuclei all have the maximum possible angle to the deuteron beam (maximum value of θ_R in Fig. 4 of I). It is seen that the measured values of both (a_2Q_2) and (a_4Q_4) are compatible with plane-wave stripping. However, since the solid curve corresponds to an improbable proton angular distribution (one not allowed by plane-wave stripping), it is likely that the relatively large deviation of the (a_4Q_4) values from the dashed curve is due to distortion effects which are expected (see I) to affect the (a_4Q_4) more than the (a_2Q_2).

An excitation function at 148° for the 0.75-MeV γ ray was measured in 50-keV intervals from 2.7 to 3.5 MeV. The total cross section for the $C^{14}(d,p_1)C^{15}$ reaction, which is shown in Fig. 6, was obtained from the differential cross section at 148° by substituting into the relation

$$\sigma(\text{mb}) = \{4\pi/[1+a_2Q_2P_2(\cos\theta)+a_4Q_4P_4(\cos\theta)]\}d\sigma_\gamma/d\Omega,$$

where $d\sigma_\gamma/d\Omega$ is the measured γ-ray differential cross section at $\theta=148°$ in units of mb/sr, and the a_2Q_2, a_4Q_4 coefficients were obtained from Eq. (5) for $\bar{E}_d=3.2$ MeV. The experimental inaccuracies in this total cross section determination are large enough so that a consideration of the effect on σ(mb) of the slight energy dependence of a_2Q_2 and a_4Q_4 which is indicated by Fig. 5 is not warranted. There is no evidence for resonances in this cross-section curve, so that the present results for the $C^{14}(d,p\gamma)C^{15}$ reaction are consistent with the cross section below a deuteron energy of 3.5 MeV being all due to the stripping mechanism. The cross section scale of Fig. 6 has an uncertainty of about 30% due almost entirely to the uncertainty in the areal density of C^{14} in the target. The possible error in the cross-section scale due to the uncertainties in the energy dependence of the γ-ray angular distribution is negligible compared to that caused by the possible error in target thickness.

B. The $Li^7(d,p\gamma)Li^8$ (0.98-MeV level) Reaction

Angular distributions of the 0.98-MeV γ ray which were obtained at deuteron energies of 2.3, 2.6, and 2.9 MeV are shown in Fig. 7. For none of these was there any evidence for a $P_4(\cos\theta)$ term. Therefore, the anisotropy, $W(0°)/W(90°)-1$, completely characterizes the angular distributions. The average value of the anisotropy obtained from these distributions is $+0.03\pm0.03$ at an average deuteron energy of 2.6 MeV. Twenty-three values of the anisotropy and total cross section were measured between $E_d=1.9$ and 3.3 MeV. These values were obtained from the yields measured in the NaI(Tl) crystals placed at 0° and 90° to the beam in the same manner as was done for the $C^{13}(d,p\gamma)C^{13}$ (3.85-MeV level) reaction (see II). The results are shown in Fig. 8.

The Li^8 ground state has $J=2^+$ while the Li^8 0.98-MeV level is known to have positive parity and $J\leqslant3$ from $Li^7(d,p)Li^8$ stripping results.[8] There is strong

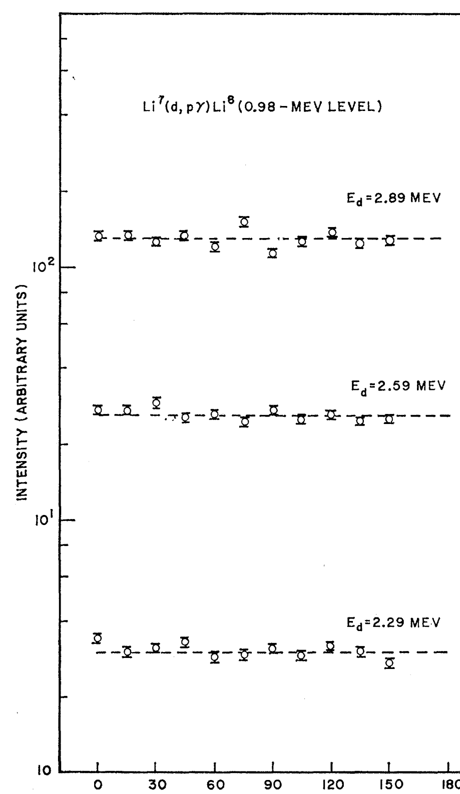

FIG. 7. Angular distributions for the Li^8 0.98-MeV γ ray. The dashed curves represent an isotropic distribution, which would be indistinguishable on the plot from the distribution predicted from plane-wave stripping theory for a $1^+\to2^+$ γ-ray transition with a channel spin ratio $(s=2)/(s=1)$ equal to 3.3 (see text).

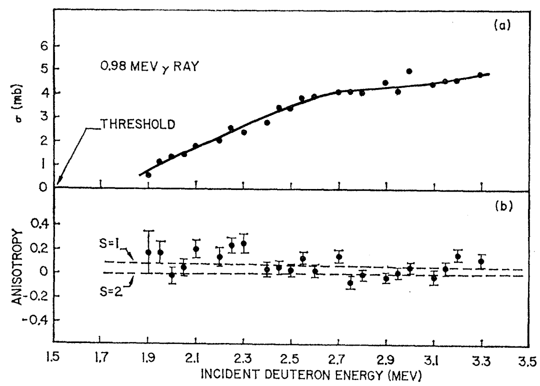

FIG. 8. Results of measurements on the yield of the 0.98-MeV γ ray from the $Li^7(d,p)Li^8$ reaction. The top curve (a) shows the total cross section for the $Li^7(d,p)Li^8$ (0.98-MeV level) reaction. The total cross section scale has an estimated uncertainty of 30%. The experimental points in (b) show the anisotropy $W(0°)/W(90°)-1$, relative to the deuteron beam. The dashed curves in (b) show the anisotropy expected if plane-wave stripping and an isotropic distribution of the outgoing protons relative to the deuteron beam are assumed. The two curves are for the two possible values of the channel spin and for a $1^+ \to 2^+$ $M1$ transition.

theoretical evidence that the Li^8 0.98-MeV level has $J^\pi = 1^+$. We shall assume this assignment in the following discussion. We shall also assume that the Li^8 $0.98 \to 0$ transition is $M1$, with the $E2$ transition having a negligible effect on the angular distribution. The angular distribution predicted by the stripping mechanism is

$$W(\theta,E_d) = 1 + 1/100[(5-x)/(1+x)]Q_2(E_d)P_2(\cos\theta),$$

where x is the ratio of the $s=2$ to the $s=1$ contribution to the cross section, s being the channel spin. The predicted anisotropy is

$$A = 3(5-x)Q_2/[200(1+x)-(5-x)Q_2].$$

The dashed curves in Fig. 8(b) show the anisotropy for $x=0$ ($s=1$ only) and $x=\infty$ ($s=2$ only) with the plane-wave stripping assumption and with Q_2 given by Eq. (2). There is evidence[4] that $3.0 \leqslant x \leqslant 3.6$ from measurements of the $Li^7(p,\gamma)Be^8$ reaction at the resonance which is purported to be the analog of the Li^8 0.98-MeV level. For this value of x the anisotropy predicted for an average deuteron energy of 2.6 MeV is 0.0047 ± 0.0012 compared to the value of $+0.03 \pm 0.03$ obtained from the present angular distribution measurements. The agreement is reasonable. The measured anisotropy values of Fig. 8(b) are not accurate enough to determine a value for x.

The deviation of the measured anisotropy from the dashed curves for deuteron energies below 2.3 MeV which is shown in Fig. 8(b) indicates a possible deviation from the simplified predictions of stripping theory given by Eq. (1) and (2). Such a deviation could not be due to nonisotropic distribution of the protons or to distortion effects in the stripping reaction, since the general result for Q_2 has the limit $Q_2 \leqslant 1$ (see I), and a better fit of the anisotropy for $E_d < 2.3$ MeV would yield $Q_2 > 1$. Thus the results of Fig. 8(b) either imply a compound-nucleus effect near 2.3 MeV or statistical fluctuations. In the latter case it would seem likely that there is an under-estimation of the errors in the anisotropy measurements for the points where the yield is lowest ($E_d < 2.3$ MeV). Since the uncertainty in the background assumed under the total absorption peak of the 0.98-MeV γ ray (see Fig. 2) is difficult to access, and since there is no evidence for compound nucleus resonances in the yield curve [Fig. 8(a)] it seems likely that the effect is best explained by statistical fluctuations. This is supported by the angular distribution measurement at $E_d = 2.3$ MeV, which yielded $A = +0.02 \pm 0.02$, in poor agreement with the anisotropy given in Fig. 8(b) for that energy, but in reasonable agreement with the theoretical predictions. It is concluded that the $Li^7(d,p\gamma)Li^8$ results are in good agreement with the predictions of stripping theory for $E_d > 2.3$ MeV but that the results for $E_d < 2.3$ MeV are rather inconclusive.

Assuming the stripping mechanism for the $Li^7(d,p)Li^8$ (0.98-MeV level) reaction, the present results can be used to show that the 0.98-MeV level is not 3^+ if the Li^8 $0.98 \to 0$ transition is $M1$. The Li^8 0.98-MeV level is formed in the $Li^7(d,p)Li^8$ stripping reaction by the capture of $l_n = 1$ neutrons.[8] Thus it has $J \leqslant 3^+$. Assuming the γ transition to the 2^+ Li^8 ground stage is dipole with negligible effect from higher multipolarities the γ-ray angular distributions expected in the present experiment, assuming the stripping mechanism, are

$$W(\theta,E_d) = 1 + \frac{1}{100}\left(\frac{5-x}{1+x}\right)Q_2(E_d)P_2(\cos\theta) \quad \text{for} \quad J=1,$$

$$W(\theta,E_d) = 1 + \frac{7}{20}\left(\frac{1-x}{1+x}\right)Q_2(E_d)P_2(\cos\theta) \quad \text{for} \quad J=2,$$

and

$$W(\theta,E_d) = 1 - 0.24Q_2(E_d)P_2(\cos\theta) \quad \text{for} \quad J=3.$$

The first of these, as has already been discussed, is in reasonable agreement with the experimental results. The theoretical distribution of $J=2$ can be made to agree with experiment by taking $x \approx 1$.

The theoretical angular distribution for $J=3$ is badly in disagreement with the experiment. The γ-ray anisotropy corresponding to this distribution is $-0.72Q_2/(2+0.24Q_2)$ and the limits on Q_2 are such (see I) that no distortion effects or proton angular distribution effects could bring the theoretical distribution into reasonable agreement with experiment. Thus, we conclude that the Li^8 0.98-MeV level has $J \leqslant 2^+$ if the assumption about the multipole character of the 0.98-MeV γ ray is correct.

IV. CONCLUSION

In the first paper of this series (I), three methods of assessing the relative importance of stripping and compound-nucleus formation near threshold were discussed. The first of these is measurement of the angular distribution of the outgoing proton or neutron. It was stated that the angular distribution of the outgoing nucleon would tend to become isotropic as threshold was approached from higher deuteron energies, for either compound-nucleus formation or stripping. This statement is incorrect for endothermic (d,p) reactions at low deuteron energies. For such reactions the Coulomb field has a large effect on the low-energy protons and they are expected to be emitted preferentially in the backward direction.[16] Thus, although the experiments would be difficult, a test of the reaction mechanism might be to study endothermic (d,p) reactions at deuteron energies low enough that the difference between the predictions of stripping theory and the compound-nucleus model would be large.

The second method discussed in I was a study of the behavior of the total cross section. It was pointed out that both reaction mechanisms predicted a $(E-E_0)^{\frac{1}{2}}$ shape for the deutron energy vs cross section curve near threshold for (d,n) reactions. Thus, the shape of the curve does not distinguish between the reaction mechanisms. Two examples of (d,n) excitation curves near threshold are available in the $B^{11}(d,n\gamma)C^{12}$ (15.1-MeV level)[17] reaction results and the $Be^9(d,n\gamma)B^{10}$ (5.16-MeV level)[18] results. The first of these was discussed in I. Both have excitation curves given, within the experimental errors, by $(E-E_0)^{\frac{1}{2}}$ for the first 70 keV above threshold.

The total cross section of the (d,p) reaction immediately above threshold is complicated by Coulomb effects. There is one case where comparison between stripping theory and experiment has been made. This is the $Li^7(d,p)Li^8$ ground-state reaction. The excitation curve has been measured[16] from 0.3 MeV (60 keV above threshold) to 2.5 MeV and in this region the total cross section, which varies by a factor of 10^5, has been fit very well by distorted wave stripping theory except for the presence of two or three resonances which are superimposed on the otherwise smoothly-rising function.[19] As pointed out by Wilkinson,[16] the shape of this excitation curve (aside from the resonances) is just the general form we expect from a compound-nucleus reaction proceeding through one or more broad resonances and/or through the tails of one or more distant resonances. Thus, although the (d,p) and (d,n) excitation curves are consistent with the smoothly varying part of the cross sections being due to the stripping mechanism, they do not distinguish between it and the compound-nucleus reaction.

The third method discussed in I for investigating the reaction mechanism near threshold in an endothermic (d,p) or (d,n) reaction is to study the angular distribution of the de-excitation γ rays relative to the deuteron beam. This is the method applied in II and in the present work. The cases studied were the $C^{12}(d,p\gamma)C^{13}$ (3.85-MeV level), $C^{14}(d,p\gamma)C^{15}$ (0.75-MeV level), and $Li^7(d,p\gamma)Li^8$ (0.98-MeV level) reactions. The previous work[17] on the $B^{11}(d,n\gamma)C^{12}$ (15.1-MeV level) was discussed in I. All of these cases were found to give results (in the deuteron energy regions investigated), which were consistent with the hypothesis that the major part of the cross section is due to the stripping mechanism, although the accuracy of the $Li^7(d,p\gamma)Li^8$ results was not good enough below 2.3 MeV to provide an adequate test.

However, only in the $B^{11}(d,n)C^{12}$ (15.1-MeV level) reaction was the γ-ray angular distribution determined within 100 keV of threshold. In the $C^{12}(d,p)C^{13}$, $C^{14}(d,p)C^{15}$, and $Li^7(d,p)Li^8$ experiments the angular distribution was obtained for lowest deuteron energies which were 400, 700, and 400 keV, respectively, above threshold. Thus, these (d,p) reactions do not investigate the reaction mechanisms as close to threshold as was desired and we can claim only a limited success for our method when applied to (d,p) reactions.

In the energy region that we have been able to investigate with the $(d,p\gamma)$ method it is expected that the stripping mechanism accounts for a large fraction of the cross section since, after all, quite a few (d,p) angular distributions have shown the characteristic stripping pattern for deuterons of 2–3 MeV. What our results do show is the very small effect the initial and final state interaction has on the $(d,p\gamma)$ results. This illustrates that the distortion effects are either small, or, more likely, that those which are present and which are conventionally given as a function of the angle of the outgoing proton, are essentially averaged out by the integration over all proton angles which occurs in the γ-ray angular distribution measurement.

In the deuteron energy range of $\sim 1.5-3.5$ MeV, theoretical expectations and the experimental results which have been attained are definite enough so that we feel the $(d,p\gamma)$ angular distribution method can be used to determine level quantum numbers and γ-ray multipolarities with some confidence. The method is illustrated in Sec. IIIB where it is shown that the present results are inconsistent with a

$$3^+ \xrightarrow{M1} 2^+$$

assignment for the Li^8 $0.98 \rightarrow 0$ transition.

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[17] R. W. Kavanagh and C. A. Barnes, Phys. Rev. **112**, 503 (1958).

[18] E. K. Warburton and L. F. Chase, Jr., Nuclear Phys. (to be published).

[19] In the $B^{11}(d,n\gamma)C^{12}$ (15.1-MeV level) and $C^{12}(d,p\gamma)C^{13}$ (3.85-MeV level) reactions, as in the $Li^7(d,p)Li^8$ (ground state) reaction, compound-nucleus resonances were observed superimposed on the smoothly varying part of the cross section. Thus, it cannot be claimed that the cross section in the region within about 2 MeV of threshold is entirely due to the stripping reaction. It should be made clear, then, that we are concerned with that part of the cross section which varies smoothly with deuteron energy.