Endothermic Deuteron Stripping Reactions. II. $C^{12}(d,p_3\gamma)C^{13*}$ Reaction*

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The total cross section of the $C^{12}(d,p_3)C^{13}$ reaction ($Q=-1.13$ Mev) to the third excited state of C^{13} at 3.85 Mev was measured for deuteron energies between 1.7 and 3.1 Mev. The cross section was obtained from the yield of the 170-kev γ ray corresponding to the electric-dipole transition between the $5/2^+$, C^{13} 3.85-Mev level and the $3/2^-$, C^{13} 3.68-Mev level. The angular distribution of the 170-kev γ ray relative to the deuteron beam was investigated for the same deuteron energy region by measuring yields at 0° and 90° to the beam. The measured anisotropy is compared to the predictions of plane-wave and distorted-wave stripping. The γ-ray anisotropy for deuteron energies between 1.7 and 2.4 Mev is in good agreement with the predictions of plane-wave stripping. Seven compound nucleus resonances corresponding to known N^{14} energy levels were observed between deuteron energies of 2.4 and 3.2 Mev. The Breit-Wigner single-level formula is used to extract resonance parameters for these levels.

1. INTRODUCTION

In the preceding paper[1] it was argued that the stripping mechanism should contribute all, or nearly all, of the cross section for many endothermic ($Q=-1$ Mev or so) stripping reactions near threshold. Several methods of investigating the relative contribution of the stripping and compound nucleus mechanisms to the cross sections 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 this paper experimental results on an endothermic $(d,p\gamma)$ reaction are presented and interpreted from the point of view of I.

The reaction investigated was $C^{12}(d,p_3\gamma)C^{13}$. The third excited state of C^{13} at 3.85 Mev decays by γ emission to the C^{13} ground state (76%) and to the C^{13} 3.68-Mev state (24%).[2] The $C^{12}(d,p)C^{13}$ reaction leading to the 3.85-Mev level was studied by means of measurements on the 170-kev γ ray corresponding to the latter transition. This reaction was chosen for several reasons: (1) the Van de Graaff used for the experiment could conveniently provide deuteron energies between 1 and 3.2 Mev, so that the Q value of -1.13 Mev for the $C^{12}(d,p)C^{13}$ (3.85-Mev level) reaction allowed an investigation of the reaction throughout the deuteron energy region of interest (threshold to several times $-Q$, see I); (2) the $\frac{5}{2}^+$, C^{13} 3.85-Mev level has a single-particle d-wave proton reduced width for the 0^+, C^{12} ground state and therefore this reaction has an intrinsically large $l_n=2$ stripping cross section; (3) the zero spin of the C^{12} ground state simplifies, to some extent, the analysis of the experimental results; (4) the threshold for the next higher C^{13} level above 3.85 Mev is at a deuteron energy of 3.25 Mev. Thus the cross section for the $C^{12}(d,p)C^{13}$ (3.85-Mev level) reaction could be obtained directly from the yield of the 170-kev γ ray for deuteron energies in the range of interest, without correcting for γ rays cascading through this level; (5) the 170-kev γ transition between the $\frac{5}{2}^+$, C^{13} 3.85-Mev level and the $\frac{3}{2}^-$, C^{13} 3.68-Mev level is chiefly electric dipole[2] and it seems reasonable to assume that it does not contain a significant contribution from $M2$ radiation. Thus, the complexity of the angular distribution function,

$$W(\vartheta)=\sum_{\nu=0}^{\nu_m} a_\nu Q_\nu P_\nu(\cos\vartheta), \tag{1}$$

of the 170-kev γ ray relative to the deuteron beam is limited by $\nu_m\leq 2$ (see I).

Several resonances corresponding to levels in N^{14} have been observed in previous investigations[2] of the $C^{12}+d$ and $B^{10}+\alpha$ reactions in the energy region covered in the present work. The $C^{12}+d$ resonances were observed for deuteron and neuteron emission and for proton emission to the ground state and first-excited state of C^{13}. In the present work no reasonances were observed within one Mev of threshold, but 7 resonances were observed at deuteron energies between 2.4 and 3.2 Mev. The information obtained pertaining to these resonances is presented here in addition to the results for lower deuteron energies which have a more direct bearing on the relative contributions of stripping and compound nuclear formation in endothermic (d,p) or (d,n) reactions near threshold.

2. EXPERIMENTAL PROCEDURE

A schematic diagram of the experimental apparatus is shown in Fig. 1. NaI(Tl) crystals, one inch diameter by one inch long, mounted on RCA 6655A photomultiplier tubes, were placed 2.4 inches from the target at 0 and 90 degrees with respect to the incident deuteron beam. The target and scintillation counters were enclosed in a lead shield 2 inches thick. The deuteron

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[1] E. K. Warburton and L. F. Chase, Jr., preceding paper [Phys. Rev. **120**, 2095 (1960)]; hereafter referred to as I.
[2] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

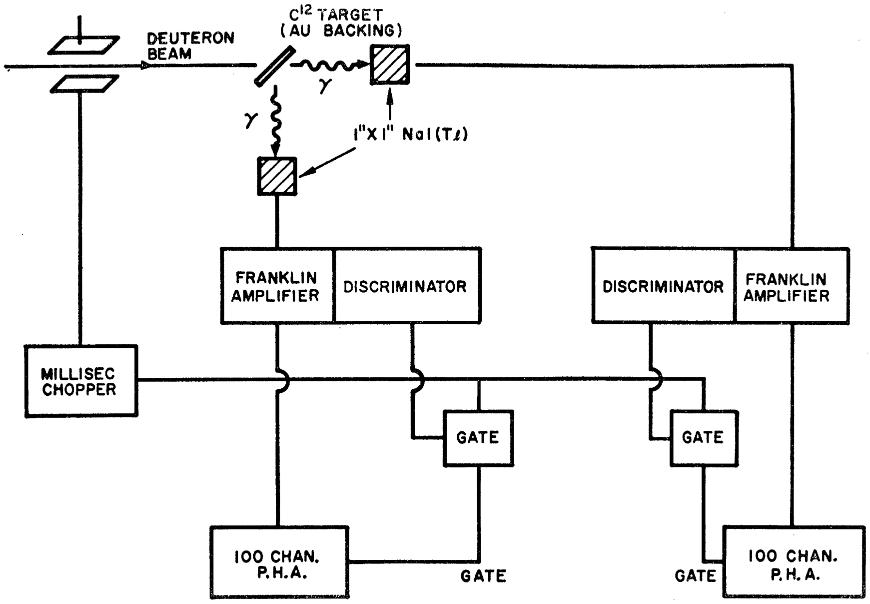

FIG. 1. A schematic diagram of the experimental arrangement used to measure the yield of the 170-kev γ rays from the $C^{12}(d,p_3\gamma)C^{13*}$ reaction at 0° and 90° to the deuteron beam.

beam was produced by the Lockheed 3.5-Mev Van de Graaff accelerator.

The pulses from the detectors were sent through linear amplifiers and into separate 100-channel analyzers. A pulse from a window discriminator after the amplifier gated the analyzer so that only the singles spectrum in the 170-kev region was displayed. This procedure was employed to reduce the dead time of the analyzer by observing the γ-ray spectrum only in the region of interest. Also, it provided a convenient method of obtaining an accurate measure of the dead time of the analyzer by comparing the number of gate pulses recorded in a fast scaler to the total number of counts presented by the analyzer. A pulse-height spectrum obtained for a deuteron energy of 2.5 Mev is shown in Fig. 2.

A beam-pulsing technique was used to reduce that part of the background under the 170-kev photopeak which was due to the Compton scattering of 511-kev γ rays in the detector and surrounding materials. Almost all of the 511-kev annihilation quanta resulted from the 10-min N^{13} positron activity produced in the accompanying $C^{12}(d,n)N^{13}$ reaction. Once each second the beam was electrostatically directed onto the target for 0.1 sec, during which time the appropriate gates (see Fig. 1) allowed the γ-ray spectra to accumulate on the pulse-height analyzers. This method achieved a reduction in the background produced by the 511-kev γ ray by approximately the duty cycle, since the yield of annihilation quanta was proportional to the average beam current, whereas the intensity of the prompt 170-kev γ rays was proportional to the instantaneous beam current.

A thin carbon target was deposited *in vacuo* by an arc discharge process onto a 0.01-in. gold backing. Special graphite spectroscopic electrodes[3] were used. The target thickness was determined from the naturally abundant C^{13} in the target by observing the width of the resonance[2] in the $C^{13}(p,\gamma)N^{14}$ reaction at $E_p=1.747$ Mev. This resonance has a negligible natural width,[2] and hence the observed width gave directly the target thickness as 7.6 kev for 1.7-Mev protons. The analyzing magnet was calibrated using $E_p=1.747$ Mev for the energy position of this resonance.

The shape of the background under the 170-Mev γ ray was determined by measuring γ-ray spectra below the $C^{12}(d,p_3\gamma)C^{13*}$ reaction threshold ($E_p=1.33$ Mev). The procedure for analyzing the data was to match this spectrum shape in the γ-ray energy region above 170 kev to the spectra obtained above threshold, as indicated in Fig. 2, and to record the peak heights above this background for each run. The intrinsic photopeak efficiency (i.e., the ratio of counts in the 170-kev photopeak to the total number of 170-kev γ rays emitted into the solid angle subtended by the scintillation crystal) was obtained from the literature except for calculated corrections for attenuation in the target backing and target chamber. The estimated uncertainty in this efficiency was 15%. As a check, the efficiency was also obtained by extrapolating the efficiencies for γ rays of 511, 279, and 192 kev obtained from calibrated sources of Na^{22}, Hg^{203}, and In^{114}, respectively. The estimated uncertainty of this method was 30%. The two methods agreed to 25%.

[3] National Carbon Company, Division of Union Carbide & Carbon Corporation.

3. RESULTS AND DISCUSSION

A. Excitation Functions and Resonance Parameters

Using the procedures described in Sec. 2, excitation curves were obtained for the yield of the 170-kev γ ray at 0° and 90° to the deuteron beam. Under the assumption that the 170-kev γ ray is electric dipole with negligible contributions from magnetic quadrupole, its angular distribution must be of the form $1+a_2Q_2P_2 \times(\cos\vartheta)$ in which case the total cross section for formation of the C^{13} 3.85-Mev level can be obtained from

$$\sigma(d,p_3)=\frac{4\pi}{3\beta N\Delta\Omega}[2Y(90°)+Y(0°)], \qquad (2)$$

where β is the branching ratio for the 170-kev γ ray, $Y(90°)$ and $Y(0°)$ are the γ-ray yields (γ/d) at 90 and 0 degrees, respectively, $\Delta\Omega$ is the solid angle (sr) subtended by the scintillation detectors, and N is the number of C^{12} nuclei per cm^2.

Using Eq. (2), the plot of $\sigma(d,p_3)$ vs E_d shown in Fig. 3(a) was obtained. The 0° and 90° excitation functions for the 170-kev γ-ray yield have the same general shape as Fig. 3(a) and so are not shown. The presence of a number of compound nucleus resonances are apparent in Fig. 3(a). The energy positions, widths, and peak cross sections of these resonances were obtained from Fig. 3(a), assuming the resonances were superimposed on the smoothly varying nonresonant background shown by the dashed line in Fig. 3(a). A summary of a Breit-Wigner single-level formula analysis of these resonances is given in Table I.

In Fig. 3(b) is shown the anisotropy $[Y(0°)/Y(90°)-1]$ of the 170-kev γ ray relative to the deuteron beam. The anisotropy has been corrected for the effects of finite solid angle. The 46 values for the anisotropy measured for deuteron energies between 1.7 and 2.4 Mev were averaged (weighed by the square of their errors) every 50 kev and plotted at the appropriate energy. Figure 3(b) clearly shows the presence of interference effects between the compound nucleus resonances and the background. Interference between the resonances may also be present. Because of this interference, an analysis in terms of the Breit-Wigner single-level formula is expected to lead to some error. The present data does not seem accurate or inclusive enough to warrant a rigorous analysis of the resonances so that the analysis was carried out assuming that the interference was negligible.

All seven resonances observed in the present work have been observed previously by both $B^{10}+\alpha$ and $C^{12}+d$,[2] but not by $C^{12}(d,p_3)C^{13*}$. The first four columns of Table I compare the energy positions and widths obtained in the present experiment to the results of previous $C^{12}+d$ work.[2] The agreement is satisfactory except for the 2.71- and 2.93-Mev resonances. No explanation for the slight discrepancy in these two cases is offered. The N^{14} excitation energies obtained from the resonance energies of the present work, using a $C^{12}+d$ Q value of 10.265 Mev,[2] are listed in the fifth column of Table I.

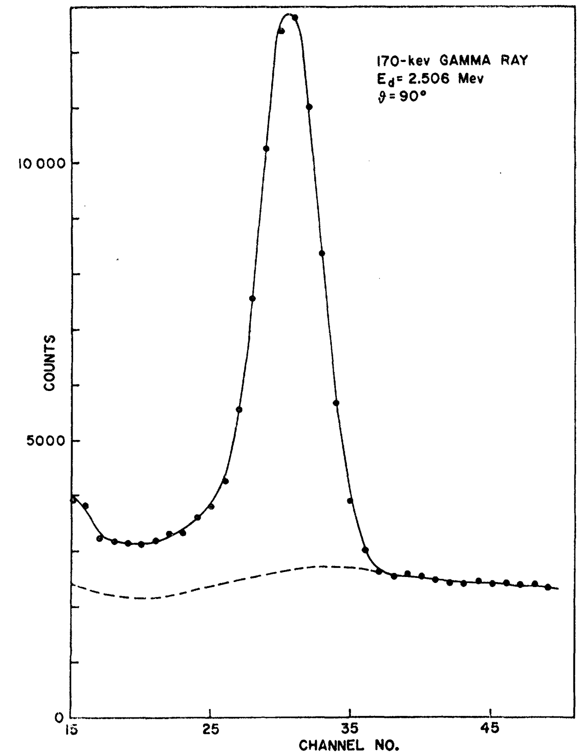

FIG. 2. A pulse-height spectrum showing the photopeak of the 170-kev γ ray from the $C^{12}(d,p_3\gamma)C^{13*}$ reaction at a deuteron energy of 2.506 Mev. The spectrum was obtained with a 1-in.×1-in. NaI(Tl) crystal at 90° to the deuteron beam. The broken curve shows the shape of the background which was assumed in extracting the yield of the 170-kev γ ray.

The values of the total cross section at the peak of the resonances were corrected for the target thickness and are listed in the seventh column of Table I. The compound nucleus factors $\Gamma_d\Gamma_{p3}/\Gamma^2$ which were derived from these cross sections, assuming the resonance spins listed in the table, are given in the following column. The compound nucleus factors $\Gamma_d\Gamma_{p3}/\Gamma^2$ for the 2.82- and 2.93-Mev resonances are in excellent agreement with the values derived for the factors from the $B^{10}+\alpha$ results of Shire *et al.*[4] For each resonance the compound nucleus factor $\Gamma_d\Gamma_{p3}/\Gamma^2$ was also obtained from the measured integrated yield $\int\sigma dE$ over the resonance and the width Γ. The $\Gamma_d\Gamma_{p3}/\Gamma^2$ obtained in this manner were in excellent agreement with those obtained from the peak cross sections, giving some justification for the use of the single-level formula.

In order to obtain the ratio of the proton partial widths to the total widths, the values of Γ_d/Γ given by

[4] E. S. Shire, J. R. Wormald, G. Lindsay-Jones, A. Lundén, and A. G. Stanley, Phil. Mag. 44, 1197 (1953).

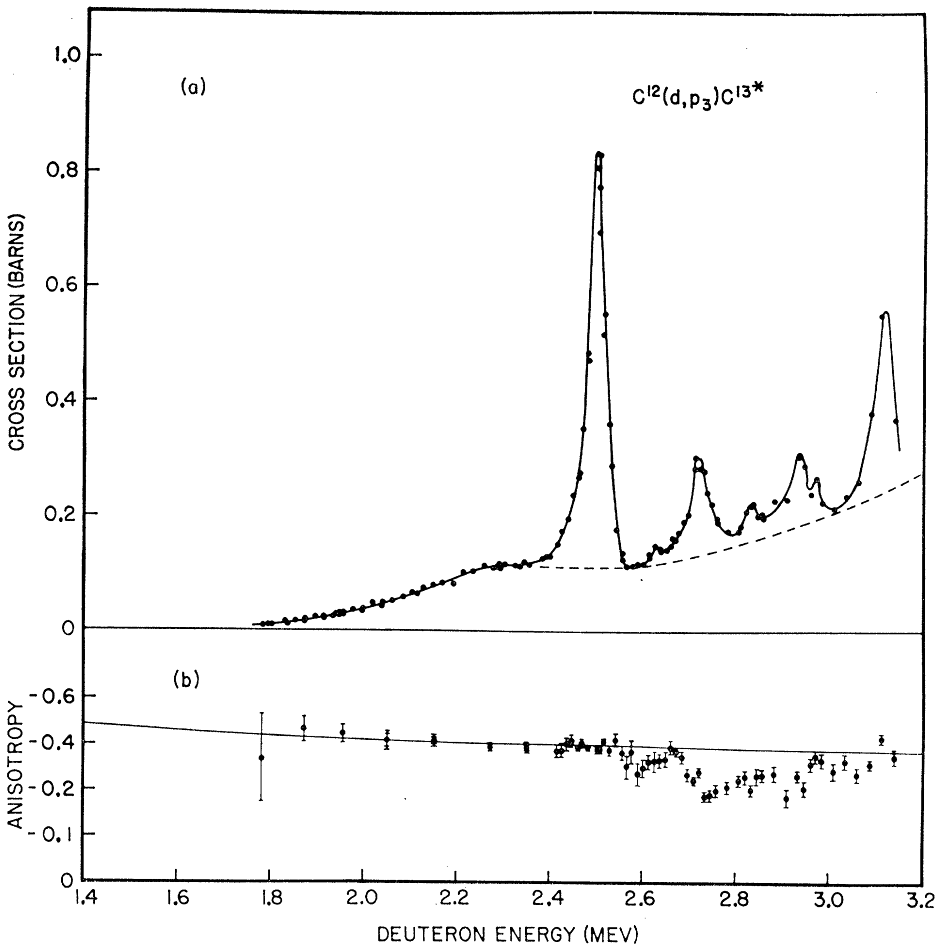

FIG. 3. Results of measurements on the yield of the 170-kev γ ray from the $C^{12}(d,p_3\gamma)C^{13}$ reaction. The top curve shows the total cross section for the $C^{12}(d,p_3)C^{13*}$ reaction. The broken curve in (a) shows the background assumed in extracting the resonance parameters (see text). The bottom curve (b) shows the anisotropy $[Y(0°)/Y(90°)-1]$ relative to the deuteron beam for the 170-kev γ ray. The solid curve in (b) shows the anisotropy expected for plane-wave stripping and an isotropic distribution of the outgoing protons relative to the deuteron beam.

McEllistrem[5] for the 2.40-, 2.71-, 2.82-, and 2.93-Mev resonances were assumed. These values of Γ_d/Γ are listed in the tenth column of Table I. The values for Γ_{p3}/Γ derived from these Γ_d/Γ and the $\Gamma_d\Gamma_{p3}/\Gamma^2$ of column eight are listed in the eleventh column in Table I. The compound nucleus factor $\Gamma_d\Gamma_{p3}/\Gamma^2$ has an upper limit of 0.25 which occurs when $\Gamma_d=\Gamma_{p3}=\frac{1}{2}\Gamma$. Thus the value of 0.33 for $\Gamma_d\Gamma_{p3}/\Gamma^2$ obtained for the 2.49-Mev resonance indicates that the total cross-section scale of Fig. 3(a) errs on the high side. The estimated uncertainty in the total cross section is 30%. The limits on Γ_d/Γ and Γ_{p3}/Γ given in Table I for the 3.11-Mev resonance were obtained from the condition $\Gamma_d(\Gamma-\Gamma_d)/\Gamma^2\geq\Gamma_d\Gamma_{p3}/\Gamma^2$.

The spin-parity assignments given in column 6 of Table I are from previous work.[2] The values of l_d and l_{p3} given in Table I are those compatible with these spin-parity assignments. The following column gives the reduced proton width, θ_{p3}^2, calculated for these l_{p3} using the values of Γ and Γ_{p3}/Γ obtained in the present work. The proton widths are given in units of $3\langle T_f\frac{1}{2}T_{zf}-\frac{1}{2}|TT_z\rangle^2\hbar^2/2MR$ where $\langle T_f\frac{1}{2}T_{zf}-\frac{1}{2}|TT_z\rangle$ is the appropriate isotopic-spin vector addition coefficient and the interaction radius is taken to be 4.7×10^{-13} cm. These proton reduced widths and the Γ_{p3}/Γ and $\Gamma_{p3}\Gamma_d/^2\Gamma$ of Table I are subject to considerable error, especially those for the weaker resonances, the estimated uncertainty being a factor of two or even more.

A reliable estimate of the single-particle d-wave proton reduced width can be obtained from the reduced width of the $\frac{5}{2}+$, N^{13} 3.56-Mev level. This width is 0.23 for an interaction radius of 4.7×10^{-13} cm.[2,6] Thus, the d-wave values for θ_{p3}^2 obtained from the 2.93- and 3.11-Mev resonances are a large fraction of the single-particle value. The $\frac{5}{2}+$, C^{13} 3.85-Mev level, which is the mirror

[5] M. T. McEllistrem, Phys. Rev. 111, 596 (1958).

[6] E. K. Warburton, H. J. Rose, and E. N. Hatch, Phys. Rev. 114, 214 (1959).

TABLE I. Resonances in the $C^{12}(d,p_3\gamma)C^{13*}$ reaction.

Present work[a] E_d(lab) (Mev)	Present work[a] $\Gamma_{c.m.}$ (kev)	Other work[b] E_d(lab) (Mev)	Other work[b] $\Gamma_{c.m.}$ (kev)	N^{14*} [c]	J^π [b]	$\sigma(d,p_3)$ (mb)	$\Gamma_d\Gamma_{p_3}/\Gamma^2$	$\Gamma_d\Gamma_{p_3}/\Gamma^2$ [d]	Γ_d/Γ [e]	Γ_{p_3}/Γ	l_d (min)	l_{p_3} (min)	$\theta_{p_3}^2$ [f]	A_{calc} [g]
2.493±8	36±8	2.502±7	40±3	12.41	4^-	710	0.33		0.55	0.61	3	1	0.11	−0.42
2.623±10	18±10	2.62±12	22±15	12.52		23								
2.710±8	51±10	2.735±6	47±3	12.59	3^+	178	0.12		0.63	0.18	2	0	0.01	−0.44
2.824±10	36±10	2.81±10	22±7	12.69	3^-	46	0.029	0.027	0.065	0.45	3	1	0.036	−0.23, −0.39
2.931±10	26±8	2.954±7	17±8	12.79	4^+	136	0.076	0.098	0.14	0.55	4	2	0.18	−0.17, −0.40
2.968±12	13±9	2.986±6	11±3	12.81	4^-	47	0.027				3	1		−0.42
3.110±10	35±20	3.123±7	28±10	12.93	4^+	320	0.19		0.8–0.2	0.2–0.8	4	2	0.06–0.26	−0.17, −0.40

[a] Errors given in kev.
[b] Summary from Ajzenberg-Selove and Lauritsen, reference 2. Errors given in kev.
[c] Values taken from present work assuming a $C^{12}+d$ Q value of 10.265 Mev (see footnote b).
[d] Shire *et al.* (reference 4).
[e] M. T. McEllistrem, (reference 5).
[f] The reduced proton width, for the minimum allowed value of l_{p_3}, given in units of $3\langle T_f\frac{1}{2}T_{zf}-\frac{1}{2}|TT_z\rangle^2\hbar^2/2MR$.
[g] Values of the anisotropy expected for the parameters listed in the table and assuming single, isolated resonances. Two values of the anisotropy for a resonance indicate the extreme values predicted for the two possible spins in the exit channel. The first value is for the higher value of the channel spin.

of the $\frac{5}{2}^+$, N^{13} 3.56-Mev level, is describable to a good approximation as a $d_{5/2}$ neutron coupled to the C^{12} ground state. The large reduced widths of the 12.79- and 12.93-Mev states of N^{14} can only be explained if these states contain a large fraction of $s^4p^8d^2$ with s^4p^8 coupling to $J=0^+$. The large values of Γ_d/Γ for both these states strongly suggests that they have $T=0$, and the configurations $d_{5/2}^2$ and $d_{3/2}^2$ cannot lead to $T=0$, $J=4^+$ states. Therefore, the results given in Table I indicate that the N^{14} 12.79- and 12.93-Mev states contain a large fraction of $s^4p^8d_{5/2}d_{3/2}$ if, in actual fact, they have $J^\pi=4^+$.

The last column of Table I gives the anisotropies calculated for compound nucleus formation assuming no interference effects. The anisotropies were calculated for the l values and spin-parity assignments given in the table. The striking fact about these anisotropies is how little they vary for different spin-parity assignments. The measured anisotropy [Fig. 3(b)] varies between -0.2 and -0.4 in the energy region of the resonances. This is the same range as for the calculated anisotropies. Because of the small variation of the calculated anisotropies and the presence of interference effects, it would seem that no meaningful conclusions on the spin-parity and l-value assignments could be made from the present results without a detailed analysis including the effects of interference.

B. Anisotropy Near Threshold

The main purpose of this work is to compare the anisotropy of the 170-kev γ ray with the predictions of stripping theory as close to threshold ($E_d=1.33$ Mev) as possible. The solid curve in Fig. 3(b) is the anisotropy calculated assuming plane-wave stripping theory and an isotropic distribution of the protons relative to the deuteron beam. The solid curve was calculated using Eqs. (3.4) and (3.7a) of I. Except for deuteron energies very close to threshold, the protons are not expected to have an isotropic distribution. However, the proton distribution would have to be exceedingly anomalous in order to cause appreciable deviations from the solid curve of Fig. 3(b). For instance, the smallest value for $-A$ corresponds to a delta function proton distribution, as can be seen from Eq. (3.6) and Fig. 3(a) of I. This value is 0.34 for $E_d=2.6$ Mev and 0.41 for $E_d=1.8$ Mev. The largest allowed value of $-A$ corresponds to a horizontal line passing through the value of $-A$ at threshold.

The anisotropy of the 170-kev γ ray is seen to be in very good agreement with the plane-wave stripping prediction for deuteron energies between 1.8 and 2.4 Mev. The 170-kev γ ray was discernible at 90° to the beam for deuteron energies down to 1.6 Mev while at 0° the γ ray could not be distinguished from the background below 1.7 Mev. Thus, it is known that the anisotropy has a large negative value at $E_d=1.6$ Mev which is 270 kev from threshold, so that the anisotropy of the 170-kev γ ray for deuteron energies between 1.6 and 2.4 Mev is consistent with the plane-wave stripping prediction. Furthermore, the $C^{12}(d,p)C^{13}$ (3.85-Mev level) excitation curve [Fig. 3(a) shows no observable resonance structure in this energy region in spite of the fact that there are several known N^{14} levels with excitation energies which correspond to deuteron energies in this range. As discussed in I, these facts are not conclusive evidence that the reaction cross section in this energy range is due to the stripping mechanism. It is possible that the reaction cross section is due to the compound nucleus mechanism with contributions from several or many broad, overlapping levels. In this case, the reaction cross section would show no resonance structure and the calculated anisotropies given in Table I illustrate the fact that the measured anisotropy could be reproduced in this case for many different combinations of spin-parity and l-value assignments. However, the most reasonable explanation of both curves of Fig. 3 is that the reaction cross section for deuteron energies below 2.4 Mev is due to stripping, while the cross section for deuteron energies between 2.4 and 3.1 Mev is due to the compound nucleus resonances listed in Table I superimposed on a nonresonant stripping background.

In the distorted wave (d,p) stripping formalism of Tobocman,[7] of Huby *et al.*,[8] and of Tobocman and Satchler,[9] compound nucleus resonances arise as the result of the final state interaction of the proton with the residual nucleus, and the stripping and compound nucleus mechanisms lose their distinction. The anisotropy of the de-excitation γ ray in a $(d,p\gamma)$ reaction is considered from this point of view in the appendix of I where the general form of the γ-ray angular distribution is given for a $(d,p\gamma)$ reaction with $\nu_m=2$ [see Eq. (1)]. It is stated in I that distortion is much more likely to decrease the magnitude of A relative to the plane-wave case than to increase it. The anisotropy curve of Fig. 3(b) is quite consistent with this remark. In Fig. 3(b) the effects of distortion on the anisotropy are only apparent in the energy region of the "resonances" and in this region the magnitude of A is decreased. It should be pointed out that the good agreement of the anisotropy with the prediction of plane-wave stripping in the energy region 1.8–2.5 Mev does not necessarily mean that there is no distortion in this energy region. This is apparent from the work of Satchler and Tobocman[9] and from the form of the anisotropy given in the appendix of I.

[7] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955); W. Tobocman, Phys. Rev. **115**, 99 (1959).

[8] R. Huby, M. Y. Refai, and G. R. Satchler, Nuclear Phys. **9**, 94 (1958).

[9] G. R. Satchler and W. Tobocman, Bull. Am. Phys. Soc. **5**, 30 (1960); and G. R. Satchler and W. Tobocman, Phys. Rev. **118**, 1566 (1960).

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Nuclear Orientation of Tb^{160}†

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Nuclear orientation of Tb^{160} in a single crystal of neodymium ethylsulphate has been observed by the anisotropic intensity distribution of the γ rays. The alignment arises from the coupling of the nuclear-magnetic and quadrupole moments with the crystal field. The spin of Tb^{160} is shown to be 3, and the spin of the 1360-kev level in Dy^{160} is 2. The nuclear moments of Tb^{160} are $|\mu|=1.60\pm0.25$ nm and $Q=+1.9\pm0.5$ barns.

I. INTRODUCTION

Nuclear orientation has become a well-established technique for measuring nuclear moments and for studying the changes in angular momentum during radioactive decay. It is usually produced by the coupling between the nuclei and the local internal fields (hfs) in crystals, which may arise from one or more of the following mechanisms:

(a) the interaction between the nuclear magnetic moment and an externally applied magnetic field, via the intermediary of an electronic moment,[1] (b) the interaction between the nuclear magnetic moment and the crystalline electric field, via an electronic moment,[2] (c) the interaction between the nuclear electric-quadrupole moment and the electric-field gradient at the nucleus.[3]

In order to obtain enough orientation for the anisotropic emission from radioactive nuclei to be measured, it is usually necessary to cool the crystal to temperatures such that the thermal energy kT is comparable with the energy separations ΔE of the nuclear magnetic levels. These splittings are most often measured by paramagnetic or nuclear-resonance spectroscopy on a stable isotope. From such determinations the choice of a suitable crystal may be made.

Mechanism (a) produces a polarization (i.e., an orientation in sense as well as direction) with respect to the applied field. Mechanisms (b) and (c) produce an alignment (orientation where parallel and antiparallel senses are equally populated) with respect to the crystal axes.

In the region of the rare earths and the actinides are found large nuclear quadrupole moments which are associated with the deformed nuclear core, as well as large electronic magnetic moments. Hence, nuclear orientation may arise from a combination of magnetic and electric hfs interactions which may act together to increase or reduce the net nuclear orientation according to their relative signs.

In this paper, experiments on the nuclear alignment and polarization of Tb^{160} in a mixed crystal of terbium and neodymium ethylsulfates are described. It was found that the magnetic interaction tended to align the nuclear spins along the c axis of the crystal, and

† This work was done under the auspices of the U. S. Atomic Energy Commission.

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[1] C. J. Gorter, Physica **14**, 504 (1948); M. E. Rose, Phys. Rev. **75**, 213 (1949).

[2] B. Bleaney, Proc. Phys. Soc. (London) **A64**, 315 (1951).

[3] R. V. Pound, Phys. Rev. **76**, 1410 (1949).