Nuclear levels in ^{161}Dy by the (d, p), (d, t), and (n, γ) reactions*

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We have investigated the levels of the ^{161}Dy nucleus with (d, p) and (d, t) reactions using 12 MeV deuterons and a broad range magnetic spectrograph, with angular distribution analysis of the (d, t) reaction using 15 MeV deuterons and a semiconductor detector telescope, and with the (n,γ) reaction over the γ-ray energy range from 25 to 6500 keV using Ge(Li) detectors and a large NaI annulus. The states observed are discussed in terms of the Nilsson model and comparisons are made with the levels in ^{163}Er and with theoretical calculations.

NUCLEAR REACTIONS ^{160}Dy(d,p), $E_d=12$ MeV; measured E_p, $\sigma(\theta)$, $\theta=75°, 95°, 115°$; ^{161}Dy deduced levels; DWBA analysis; enriched target; magnetic spectrograph. ^{162}Dy(d,t), $E_d=12$ MeV; measured E_t, $\sigma(\theta)$, $\theta=85°, 110°$; ^{161}Dy deduced levels; DWBA analysis; enriched target; magnetic spectrograph. ^{162}Dy(d,t), $E_d=15$ MeV, measured E_t, $\sigma(\theta)$, $\theta=30-100°$; deduced l values; ^{161}Dy deduced levels; DWBA analysis, enriched target; counter telescope. ^{160}Dy(n,γ), E_n=thermal; measured E_γ, I_γ, $E_\gamma=25-1600$ keV and 4.5–6.5 MeV; ^{161}Dy deduced levels; enriched target; Ge(Li) detectors. ^{161}Dy levels, J, π, Nilsson assignments.

I. INTRODUCTION

This paper describes the results of several experiments involving reactions leading to the nucleus ^{161}Dy, as well as a comparison of these results with other experimental work on ^{163}Er and with theoretical calculations for this isotone. Both the (d,p) and (d,t) reactions have been studied at several angles with 12 MeV incident deuterons and the reaction products analyzed with a high resolution magnetic spectrograph. In addition, angular distributions have been measured for the (d,t) reaction at 15 MeV with solid state detectors. Finally, the γ-ray spectra from thermal-neutron capture on ^{160}Dy have been measured between 25 keV and the neutron binding energy with Ge(Li) detectors.

We have been particularly influenced by the (d,p) and (d,t) measurements of Grotdal, Nybø, and Elbek[1] and have used their results extensively in our analysis. Experimental work on this nucleus is, however, summarized in the review of Bunker and Reich[2] and in the review of Tuli.[3] Since these reviews, the only paper of significance to this study are measurements of high spin states[4] and an interpretation[5] of the mixing of the positive parity states in ^{161}Dy. Some of the results of the present work have been reported earlier[6] and some are quoted in Ref. 2.

II. EXPERIMENTAL TECHNIQUES

The techniques used in the magnetic spectrograph studies and the (n,γ) experiments are described elsewhere[7] and more complete references are given there. The (n,γ) experiments were done with a 100 mg sample of Dy_2O_3 enriched to 85.4% ^{160}Dy which was obtained from the Stable Isotopes Division of the Oak Ridge National Laboratory. The product of isotopic composition and cross section yields the following capture percentages for the various Dy isotopes in the target: 48% in ^{160}Dy, 24% in ^{161}Dy, 4% in ^{162}Dy, 2% in ^{163}Dy, and 21% in ^{164}Dy.

The counter telescope studies of the (d,t) reaction were done with a 15 MeV deuteron beam from the Los Alamos tandem Van de Graaff accelerator. An on-line computer[8] acquired the data and performed particle identification calculations for each detected particle by use of the relation[9]

$$m \propto (E+\Delta E)^{1.73} - (E)^{1.73} . \qquad (1)$$

Here, ΔE is the energy loss of the charged particle in traversing the "ΔE" counter (a Si surface-barrier detector 250 μm thick) and E is the residual energy (as measured with a Si surface-barrier detector 2000 μm thick). The detector telescope was cooled to $-10°$ C and the overall energy resolution was approximately 27 keV (full width at half maximum). The computer program sorted total energy pulses ($E+\Delta E$) into three spectra: one each for protons, deuterons, and tritons. The proton energy spectra were not analyzed. Since the elastic scattering data, on which the cross section measurements were based, were accumulated simultaneously with the (d,t) data, there were no difficulties due to the small and nonuniform target deposit, as there were in the case of the magnetic spectrograph data. The peaks in the data were fitted to sums of Gaussians by a nonlinear least-squares program.[10] The spectrum was found to be highly complex and the centroids of many of the weaker unresolved peaks were held fixed at values corresponding to the known energies of the states so that the peak areas could be determined most accurately.

III. RESULTS

A. Direct reaction data

Magnetic spectrograph data were taken at angles of 75°, 95°, and 115° for the ^{160}Dy$(d,p)^{161}$Dy reaction and at 85° and 110° for the ^{162}Dy$(d,t)^{161}$Dy reaction. A composite plot of the 95° (d,p) data and the 110° (d,t) data is shown in Fig. 1. The associated Nilsson assignments are also shown in this figure. An energy resolution of approximately 15 keV was obtained for both reactions at all angles. Excitation energies were measured relative to the large peak at 367 keV. The Q values are based on ^{12}C$(d,p)^{13}$C for the (d,p) spectra and elastic scattering for the (d,t) spectra. The separately averaged (d,p) and (d,t) energies and the cross sections for the various states are given in Table I. In this table the errors in level energies (shown underlined) have been estimated from the spread in values obtained in various runs and from comparison with the more accurate energies determined by the (n,γ) experiments. The ground-state Q value for the ^{160}Dy$(d,p)^{161}$Dy reaction was measured to be 4231 ± 10 keV, while that for the ^{162}Dy$(d,t)^{161}$Dy reaction was found to be -1943 ±10 keV. These values are in good agreement with the neutron binding energy of 6452.5 ± 2.5 keV obtained in the present (n,γ) studies and with Q values calculated from a recent mass adjustment.[11]

Angular distributions for the ^{162}Dy$(d,t)^{161}$Dy reaction, as measured with the counter telescope, are presented in Table II. A typical spectrum is shown in Fig. 2. The solid curves are the results of a distorted-wave Born-approximation calculation.[12] The l-value assignments to the various levels are given in the table, and typical angular distributions are shown in Fig. 3. Unfortunately, counting rate limitations prevented taking usable data at angles smaller than 30°, making it im-

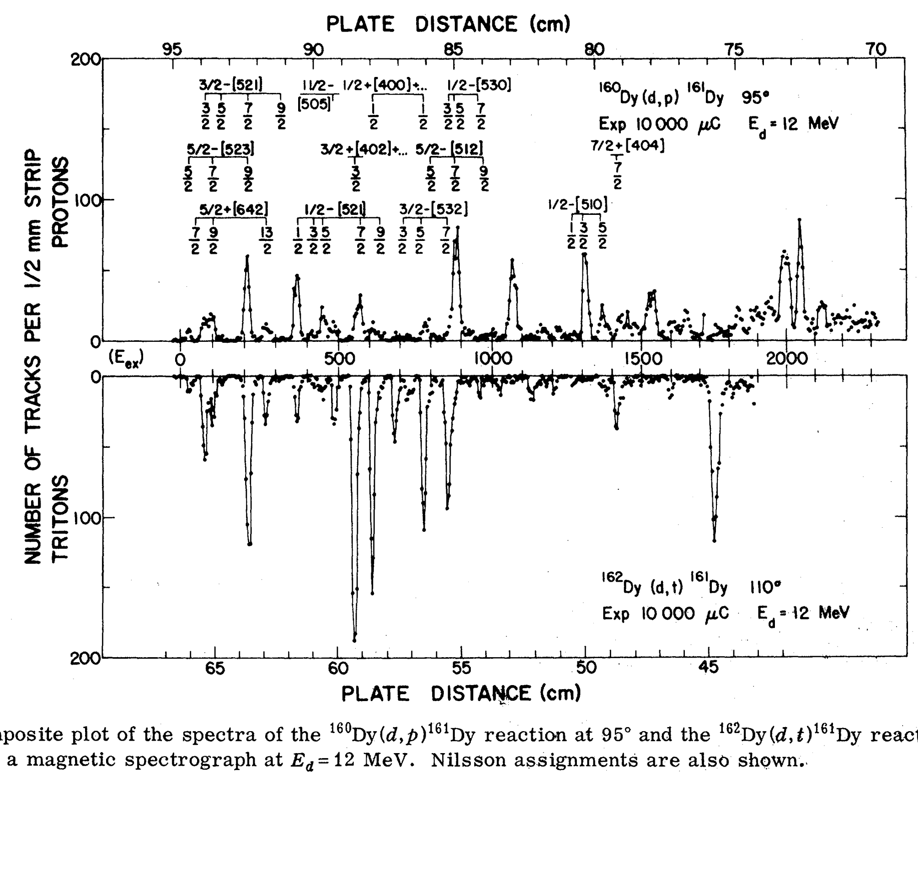

FIG. 1. Composite plot of the spectra of the ^{160}Dy$(d,p)^{161}$Dy reaction at 95° and the ^{162}Dy$(d,t)^{161}$Dy reaction at 110° as measured with a magnetic spectrograph at $E_d = 12$ MeV. Nilsson assignments are also shown.

TABLE I. Summary of data on the energy levels of ^{161}Dy.

Energy (keV)	^{161}Dy energy levels I^π	Nilsson assignment	^{160}Dy$(n,\gamma)^{161}$Dy, *H*1, *EN*. E_γ (keV)	E_{ex} (keV)	σ^a (b)	^{160}Dy$(d,p)^{161}$Dy E_{ex} (keV)	$d\sigma/d\Omega$ (μb/sr) 75°	95°	115°	^{162}Dy$(d,t)^{161}$Dy E_{ex} (keV)	$d\sigma/d\Omega$ (μb/sr) 80°	110°	l^b
0.000	$\frac{5}{2}^+$	$\frac{5}{2},\frac{5}{2}^+[642]$											
25.664 13	$\frac{5}{2}^-$	$\frac{5}{2},\frac{5}{2}^-[523]$				23 3	7	18	18	26 4	35	23	3
43.825 11	$\frac{7}{2}^+$	$\frac{7}{2},\frac{5}{2}^+[642]$				43 6	4	5		46 7	5		
74.562 7	$\frac{3}{2}^-$	$\frac{3}{2},\frac{3}{2}^-[521]$	6377.3	75.2 8	0.10	74 2	41	44	15	74 3	243	132	1
100.42 3	$\frac{9}{2}^+$	$\frac{9}{2},\frac{5}{2}^+[642]$											
103.045 8	$\frac{7}{2}^-$	$\frac{7}{2},\frac{5}{2}^-[523]$				100 2	69	54	25	100 3	106	70	3
131.743 9	$\frac{5}{2}^-$	$\frac{5}{2},\frac{3}{2}^-[521]$				124 3	14	6		127 4	12	11	(3)
201.09 2	$\frac{9}{2}^-$	$\frac{9}{2},\frac{5}{2}^-[523]$				199 8			10	194 12	40	9	
212.94 2	$\frac{7}{2}^-$	$\frac{7}{2},\frac{3}{2}^-[521]$				211 2	82	162	79	212 3	358	278	3
268 2	$\frac{13}{2}^+$	$\frac{13}{2},\frac{5}{2}^+[642]$				267 2	33	32	41	269 3	71	69	6
319.16 11	$\frac{9}{2}^-$	$\frac{9}{2},\frac{3}{2}^-[521]$				314 2	14	5	5	313 3	14	5	(5)
366.95 2	$\frac{1}{2}^-$	$\frac{1}{2},\frac{1}{2}^-[521]$		367.0 3	11.18	367 2	193	132	77	367 3	107	66	1
418.19 2	$\frac{3}{2}^-$	$\frac{3}{2},\frac{1}{2}^-[521]$	6085.5	418.3 5	1.42	419 3	42	15	11	420 3	16	7	1
451.42 2	$\frac{5}{2}^-$	$\frac{5}{2},\frac{1}{2}^-[521]$	6034.2			450 2	52	60	25	446 3	27	35	(3)
488 3	$\frac{11}{2}^-$	$\frac{11}{2},\frac{11}{2}^-[505]$				490 5	13	31	6	487 3	46	69	(5)
550.17 3	$\frac{3}{2}^+$	$\frac{3}{2},\frac{3}{2}^+\{[402]+[651]\}$				552 2	36	38	18	551 3	470	382	2
572.30 7	$\frac{7}{2}^-$	$\frac{7}{2},\frac{1}{2}^-[521]$				570 2	49	67	66	567 3	45	24	
607.51 4	$\frac{1}{2}^+$	$\frac{1}{2},\frac{1}{2}^+\{[400]+[660]\}$				608 2	26	27	19	608 3	419	291	(0)
630 3	$\frac{9}{2}^-$	$\frac{9}{2},\frac{1}{2}^-[521]$				630 4	50	26	16	631 3	10	19	5
678.35 5	$(\frac{7}{2}^-)$					681 4	11	6	8	680 3	96	89	(4)
710.57 2	$\frac{3}{2}^-$	$\frac{3}{2},\frac{3}{2}^-[532]$								716 3	34	29	(1)
720.95 5	$\frac{5}{2}^-,\frac{7}{2}^+$					718 4	9	5	6				
732 4										732 4	26	21	
772.55 6	$\frac{5}{2}^-$	$\frac{5}{2},\frac{3}{2}^-[532]$											
776.99 5	$\frac{1}{2}^+$	$\frac{1}{2},\frac{1}{2}^+\{[400]+[660]\}$	5675.5	777.0 5	1.61	778 3	58	35	30	774 3	267	221	(0)
798.22 9	$\frac{5}{2}^-$	$\frac{5}{2},\frac{5}{2}^-[512]$				803 2	8	9	8	793 3	30	26	(3)

TABLE I (*Continued*)

Energy (keV)	^{161}Dy energy levels I^{π}	Nilsson assignment	^{160}Dy$(n,\gamma)^{161}$Dy, *H1*, *EN*. E_{γ} (keV)	E_{ex} (keV)	σ^{a} (b)	^{160}Dy$(d,p)^{161}$Dy E_{ex} (keV)	$d\sigma/d\Omega$ (μb/sr) 75°	95°	115°	^{162}Dy$(d,t)^{161}$Dy E_{ex} (keV)	$d\sigma/d\Omega$ (μb/sr) 80°	110°	l^{b}
825.53 5	$\frac{5}{2}^-, \frac{7}{2}^-$									823 6	18	16	
857.50 8	$\frac{7}{2}^-$	$\frac{7}{2}, \frac{3}{2}^-[532]$											
858.69 6	$\frac{3}{2}^-$	$\frac{3}{2}, \frac{1}{2}^-[530]$	5594.3	858.2 6	0.48	857 2	41	33	20	854 3	198	185	1
875.63 6	$\frac{5}{2}^-$	$\frac{5}{2}, \frac{1}{2}^-[530]$								871 4	36	58	(3)
882 2	$\frac{7}{2}^-$	$\frac{7}{2}, \frac{5}{2}^-[512]$				882 2	165	218	166				
928 5						931 2	4	18	6	924 4	8	12	
956 4	$\frac{7}{2}^-$	$\frac{7}{2}, \frac{1}{2}^-[530]$								956 4	31	23	
973 4	$\frac{9}{2}^-$	$\frac{9}{2}, \frac{3}{2}^-[532]$								973 4	10	5	
990 2	$\frac{9}{2}^-$	$\frac{9}{2}, \frac{5}{2}^-[512]$				990 2	15	17	15				
1005.22 10	$\frac{5}{2}^-$									1008 4	8	8	
1026 4	$\frac{5}{2}^-, \frac{7}{2}^-$									1026 4	20	20	3
1040 3						1038 2	10	8	11	1043 4	6	4	
1132 4	$\frac{7}{2}^+, \frac{9}{2}^+$									1132 4	19	31	4
1145 2						1145 2	33	9	12				
1166 2						1166 2	17	27	15				
1180 4										1180 4	7	12	
1202.35 5	$\frac{5}{2}^+$									1206 4	13	19	
1214 2						1214 2	13	22	15				
1240 2						1240 2	19	6	6				
1268.58 10	$\frac{1}{2}^-$	$\frac{1}{2}, \frac{1}{2}^-[510]$	5182.9	1269.6 7	1.01	1271 2	14	9	13	1272 4	8	14	(1)
1301.69 15	$\frac{3}{2}^-$	$\frac{3}{2}, \frac{1}{2}^-[510]$	5149.5	1303.0 9	0.83	1306 2	200	165	96				
1358.0 6	$(\frac{5}{2}^-)$	$\frac{5}{2}, \frac{1}{2}^-[510]$	5094.5	1358.0 6	2.82	1361 2	42	52	35				
1376.18 7	$\frac{3}{2}^+$		5073.2	1379.3 6	2.69	1382 2	28	21	31	1382 4	7	23	2
1417 2	$\frac{7}{2}^+$	$\frac{7}{2}, \frac{7}{2}^+[404]$				1419 2	51	48	34	1415 4	57	72	4
1434.9 6	$\frac{1}{2}^-, \frac{3}{2}^-$		5017.6	1434.9 6	2.33					1435 4	22	21	(1)
1445 2	$\frac{7}{2}^-$	$\frac{7}{2}, \frac{1}{2}^-[510]$				1445 2	49	36	42				
1459 6										1459 6	8	12	
1468.7 9			4983.8	1468.7 9	0.37	1473 2	41	30	37				

[a] These cross-section errors contain at least two contributions: a statistical error for each peak involving the spectrum analysis and the number of counts in the peak; and a relatively constant error involving the relationship of the peak intensity to the cross section. We estimate the total error for the strongest peaks to be about 20% (with approximately similar contributions coming from each of the major sources of error) and about 50% for the weakest peaks (with almost the entire contribution from the statistical error).

[b] The l values shown are assigned from the counter telescope data on the ^{162}Dy$(d,t)^{161}$Dy reaction at 15 MeV.

TABLE II. Angular distributions of the ^{162}Dy$(d,t)^{161}$Dy reaction at 15 MeV.

Energy (keV)	l	30°	35°	40°	45°	50°	55°	60°	70°	80°	90°	100°
		$d\sigma/d\Omega$ (μb/sr) [a]										
26	3	36 7	43	43 7	50	47 8	51	32 4	28	23	14	13
75	1	373 47	384	341 14	361	343 14	278	229 5	182	120	65	72
103	3	116 18	92	87 4	107	115 10	112	92 4	88	57	40	55
132	(3)	20 10	10	15 10	17	18 4	22	13 4	14	5	7	5
213 [b]	3	355 4	359	348 20	455	458 4	373	339 6	305	231	149	142
268	6	27 4	29	48 12	92	93 12	84	77 7	86	79	49	47
319	(5)	15 8	12	15 10	12	21 6	16	16 4	22	11	7	15
367	1	190 7	181	157 4	181	176 8	177	119 4	80	70	46	37
418	1	41 9	36	57 8	57	45 4	46	27 4	32	29	11	11
451	(3)	23 4	33	35 10	33	38 4	25	31 4	32	36	31	51
488	(5)	20 6	35	58 7	76	81 5	59	69 4	71	85	55	64
550	2	573 23	533	593 52	729	700 18	662	586 17	500	414	305	277
608	(0)	492 4	482	624 46	805	678 19	521	427 5	431	313	197	194
630	5	54 23	53	114 8	102	86 26	54	50 14	45	57	44	60
678	(4)	125 13	113	153 17	169	167 16	168	140 4	138	120	97	100
725 [b]	(1)	79 14	60	116 32	98	84 14	73	72 4	64	39	26	30
777	(0)	434 38	414	578 40	710	591 11	437	375 11	391	277	176	185
810 [b]	(3)	35 7	62	52 8	91	59 5	55	49 5	50	37	25	31
859	1	492 33	440	449 78	508	474 47	409	335 20	262	218	146	120
876	(3)	34 11	27	55	64	57 17	17	56 20	49	41	21	34
1026	3	45 4	45	36	77	61 4	50	38 8	31	27	21	20
1132	4	37 11	34	39	44	39 4	34	38 14	31	34	22	23
1195 [b]		35 4	26	46	50	24 4	14	27 4	23	38	24	14
1269	(1)	32	21		14	17 4	30	16 6	13	16	7	9
1376	2	43 4	44	41	56	54 4	36	36 7	30	32	9	17
1417	4	147 6	133	156 6	150	170 4	182	157 6	113	126	105	93
1450 [b]	(1)	37 11	37		58	42	21	18 9	17	15		

[a] The 30°, 40°, 50°, and 60° runs were repeated. The numbers shown underlined for these angles are the observed deviations from the mean, or 4 μb/sr, whichever is larger.

[b] These states are known to be multiplets from the spectrograph data but cannot be separated in the counter telescope data.

possible to use the characteristic forward peaking of the angular distributions[13] to confirm the identification of the $l=0$ states.

B. (n,γ) data

The high energy (n,γ) data were taken with a 13 cm^3 Ge(Li) detector and a split NaI(Tl) annulus in

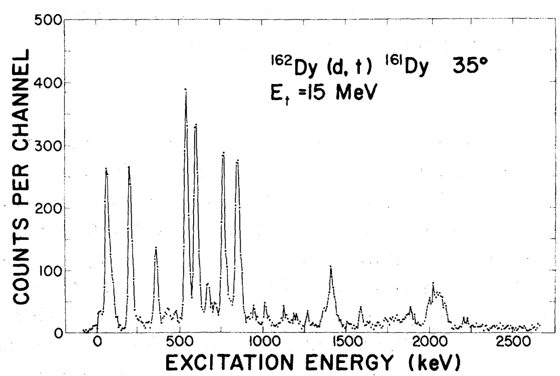

FIG. 2. Spectrum of the ^{162}Dy$(d,t)^{161}$Dy reaction at 35° as measured with a counter telescope at $E_d=15$ MeV.

the "double escape" mode.[7] A segment of the high-energy γ-ray spectrum is shown in Fig. 4. The energies and cross sections of the observed γ rays in the high energy spectrum are shown in Table I. These are based on a calibration with a nitrogen target of known mass.[7] In order to keep the length of the table to a minimum, impurity lines are not included. An independent check on cross section accuracies is available because the 6622 keV line in ^{162}Dy appears as a large impurity peak in this spectrum. Cross section errors are not shown since for all but the weakest transitions, the statistical errors are smaller than the 20% uncertainty in the cross section calibration. The intensity corresponding to the peak area was measured and the cross section of the line was determined. The result agreed with the published value[14] to within 14%.

Figure 5 shows a portion of the low-energy γ-ray spectrum from the (n,γ) reaction, taken with a high resolution detector [0.5 cm^3 Ge(Li)]. The low energy γ-ray data are presented in Table III which also incorporates the data taken with the

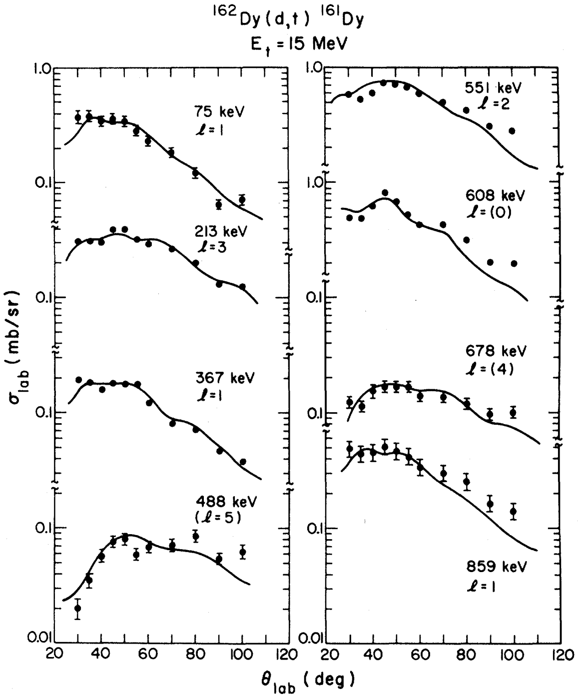

FIG. 3. Selected angular distributions for the ^{161}Dy-$(d,t)^{161}$Dy reactions at $E_d = 15$ MeV.

13 cm^3 detector and the annulus in anticoincidence as a "Compton suppression spectrometer."[7] The intensities of data taken with the high resolution detector were normalized to the ^{163}Dy impurity peak at 250.88 keV as measured with the larger detector. The units of intensity in the table are referred to a calibration with a gold target of known mass and are nominally barns. However,

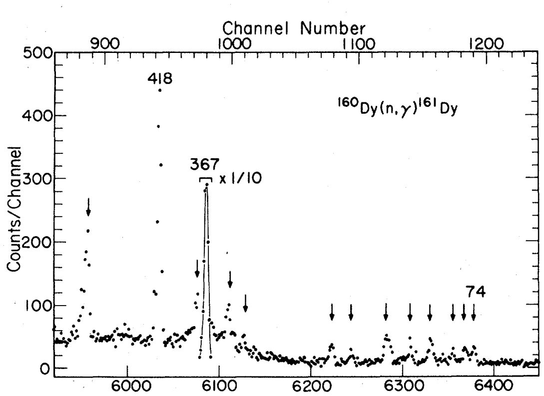

FIG. 4. A portion of the high-energy spectrum for the ^{160}Dy$(n,\gamma)^{161}$Dy reaction. The numbers labeling some of the peaks are the corresponding excitation energies in keV. The unlabeled peaks are due to impurities. The peak at $E_{exc} = 367$ keV has been reduced in amplitude by a factor of 10. The spectrum is measured with a Ge(Li) detector in the "double escape" mode, see Ref. 1.

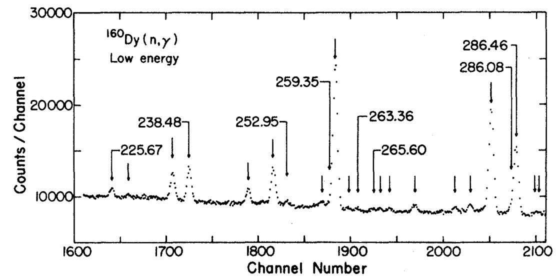

FIG. 5. A portion of the low-energy spectrum for the ^{160}Dy$(n,\gamma)^{161}$Dy reaction as measured with a Ge(Li) detector. All peaks are marked; the unlabeled peaks are those due to impurities in the target. Peaks due to capture into ^{161}Dy are marked with the corresponding γ-ray energy.

they are based on a relative efficiency calibration for the larger Ge(Li) detector which was done approximately six months before the data were taken. The detector efficiency calibration was redone a similar time after the present data were taken. The results show that a large decrease ($\approx 2\times$) in absolute efficiency had occurred during the period between calibrations. The efficiency curve for the larger Ge(Li) detector also had a more rapid falloff in efficiency for energies above 500 keV. Fortunately, the present data are not subject to error from the decrease in absolute efficiency but are sensitive to the change in shape of the relative efficiency calibration curve. If the change in efficiency occurred at a time between the initial efficiency determination and the taking of the data, then there could be a systematic underestimation of γ-ray intensities at energies above 500 keV. Below this energy there are no significant differences. The error could be as large as a factor of 2 at energies near 800 keV. It should, however, be pointed out that no allowance for these possible errors has been made in Table III. Table III also shows all of the possible placements of each γ ray. γ rays which are partially due to contaminants are also indicated.

IV. DISCUSSION

The level scheme deduced from these experiments is shown in Fig. 6. A plot of the data of Fig. 1 in bar graph form is shown at the margin for convenience. The widths of the lines representing γ rays are proportional to the square root of the transition intensity. An asterisk on a transition energy indicates either a multiple assignment, or a line which is partially obscured by an impurity, or both. The spin and parity assignments made in this work are also shown on the level scheme. Table I presents more detailed

TABLE III. Low-energy data on the $^{160}Dy(n,\gamma)^{161}Dy$ reaction.

E_γ (keV)	ΔE_γ (keV)	I_γ[a]	ΔI_γ	Initial states			E_γ (keV)	ΔE_γ (keV)	I_γ[a]	ΔI_γ	Initial states			
25.69	0.03	2.13	0.32	25			578.13	0.30	0.06	0.01	678	1376		
28.83	0.06	0.01	0.01	131			587.09	0.34	0.07	0.02	1005			
43.80	0.02	0.35	0.05	43			589.25	0.06	0.59	0.15	720			
48.90	0.02	4.82	0.87	74			598.95	0.16	0.14	0.03	1376			
50.41[b]	0.02	0.70	0.62				603.75	0.05	0.56	0.14	678	1376		
57.18	0.01	0.34	0.05	131			607.50	0.04	1.06	0.27	607	710		
59.24	0.02	0.03	0.01	103	857		609.99	0.15	0.12	0.03	710			
74.56	0.01	2.29	0.35	74	1376		624.43	0.06	0.33	0.08	825			
77.37[b]	0.05	0.10	0.07	103	798	875	644.53[b]	0.12	0.40	0.20	857			
81.20	0.04	0.26	0.06	212			653.09	0.55	0.03	0.01	678			
87.02[b]	0.08	0.04	0.01				655.20	0.12	0.28	0.07	1376			
87.88	0.02	0.09	0.01	131			672.36[b]	0.14	0.62	0.31	772			
98.98	0.02	0.02	0.01	201			678.20[b]	0.12	0.64	0.32	678			
98.73[b]	0.05	0.03	0.01	550	776	875	687.68[b]	0.18	0.43	0.21				
100.64[b]	0.10	0.01	0.01	100	201		698.98	0.11	0.32	0.08				
101.99	0.02	0.07	0.01				702.43	0.05	0.82	0.21	776			
103.05	0.01	0.25	0.04	103	710	875	721.38	0.28	0.03	0.01	720			
106.11	0.02	0.03	0.01	131	319	678	726.95	0.06	0.46	0.12	858			
109.83	0.06	0.02	0.01	212			729.97	0.06	0.58	0.15	1301			
112.52	0.03	0.02	0.01	212			736.06	0.07	0.16	0.04				
135.76	0.06	0.01	0.01				751.34	0.47	0.13	0.03	776	825	1202	1301
138.39	0.02	0.12	0.02	212			757.09	0.20	0.09	0.02	857			
157.26	0.02	0.07	0.01	201			764.86	0.14	0.12	0.03				
171.23	0.06	0.07	0.02				772.56	0.09	0.51	0.13	772	798	875	
172.75[b]	0.05	0.15	0.03				779.13	0.15	0.12	0.03				
173.82	0.07	0.10	0.02	1376			781.73	0.11	0.20	0.05	825			
175.26	0.05	0.10	0.02	201			784.15	0.19	0.08	0.02	858	1202		
192.50	0.07	0.06	0.02				790.49	0.16	0.21	0.05				
216.05	0.11	0.03	0.01	319			798.49[b]	0.16	0.47	0.23	798			
225.67	0.04	0.13	0.03				804.36	0.25	0.21	0.05	1005			
238.48	0.02	0.55	0.08	451			812.78	0.15	0.03	0.01				
252.95[b]	0.14	0.11	0.07	572			825.60	0.08	0.32	0.08	825			
259.35	0.12	0.12	0.05				901.93	0.24	0.13	0.03	1005	1268		
263.36[b]	0.10	0.04	0.04	1268			966.36	0.43	0.04	0.01				
265.60	0.17	0.02	0.02				975.75[b]	0.24	0.24	0.12				
286.08[b]	0.14	0.12	0.11				1005.01[b]	0.16	0.42	0.21	1005			
286.46	0.03	1.98	0.30	418	858		1031.23	0.19	0.11	0.03				
292.38	0.02	6.11	0.93	366	710		1098.00	0.19	0.08	0.02				
319.67	0.03	0.91	0.14	451			1101.90	0.26	0.04	0.01	1202			
324.02	0.07	0.02	0.02				1136.77	0.19	0.11	0.03	1268			
341.33	0.07	0.32	0.09	366			1234.59	0.17	0.12	0.03				
343.62	0.02	1.94	0.29	418	710	1202	1239.86	0.28	0.06	0.01				
347.43[b]	0.16	0.27	0.13				1247.59	0.15	0.12	0.03				
348.13[b]	0.20	0.25	0.12	451			1283.21	0.11	0.46	0.11				
376.97[b]	0.16	0.12	0.06	451	1202		1301.83	0.25	0.03	0.03	1301	1376		
386.04[b]	0.06	1.72	0.52				1304.06	0.13	0.27	0.07				
392.68[b]	0.08	0.35	0.35	418	1268		1311.71	0.30	0.06	0.01				
396.76[b]	0.16	0.17	0.11				1316.87	0.21	0.07	0.02				
401.55[b]	0.14	0.20	0.18	720			1319.60	0.23	0.06	0.01				
418.55[b]	0.24	0.19	0.09	418	550		1329.63	0.31	0.10	0.03				
439.98[b]	0.36	0.08	0.04	858			1332.25	0.23	0.14	0.03	1376			
455.11	0.36	0.02	0.01	1005			1360.77	0.18	0.13	0.03				
491.66	0.32	0.09	0.02	858	1202	1268	1463.17	0.23	0.10	0.02				
517.81	0.10	0.10	0.03				1516.95	0.21	0.14	0.04				
550.14	0.04	0.82	0.21	550			1529.03[b]	0.34	0.22	0.12				
556.48[b]	0.14	0.25	0.13	875			1556.45	0.19	0.34	0.09				
566.86	0.18	0.36	0.09											

[a] The units of intensity are normally barns but there may be large errors (≈2×) above 500 keV and the normalization below that energy may be in error by as much as 50%. See text.

[b] These γ rays are known to be partially obscured by lines from other Dy isotopes.

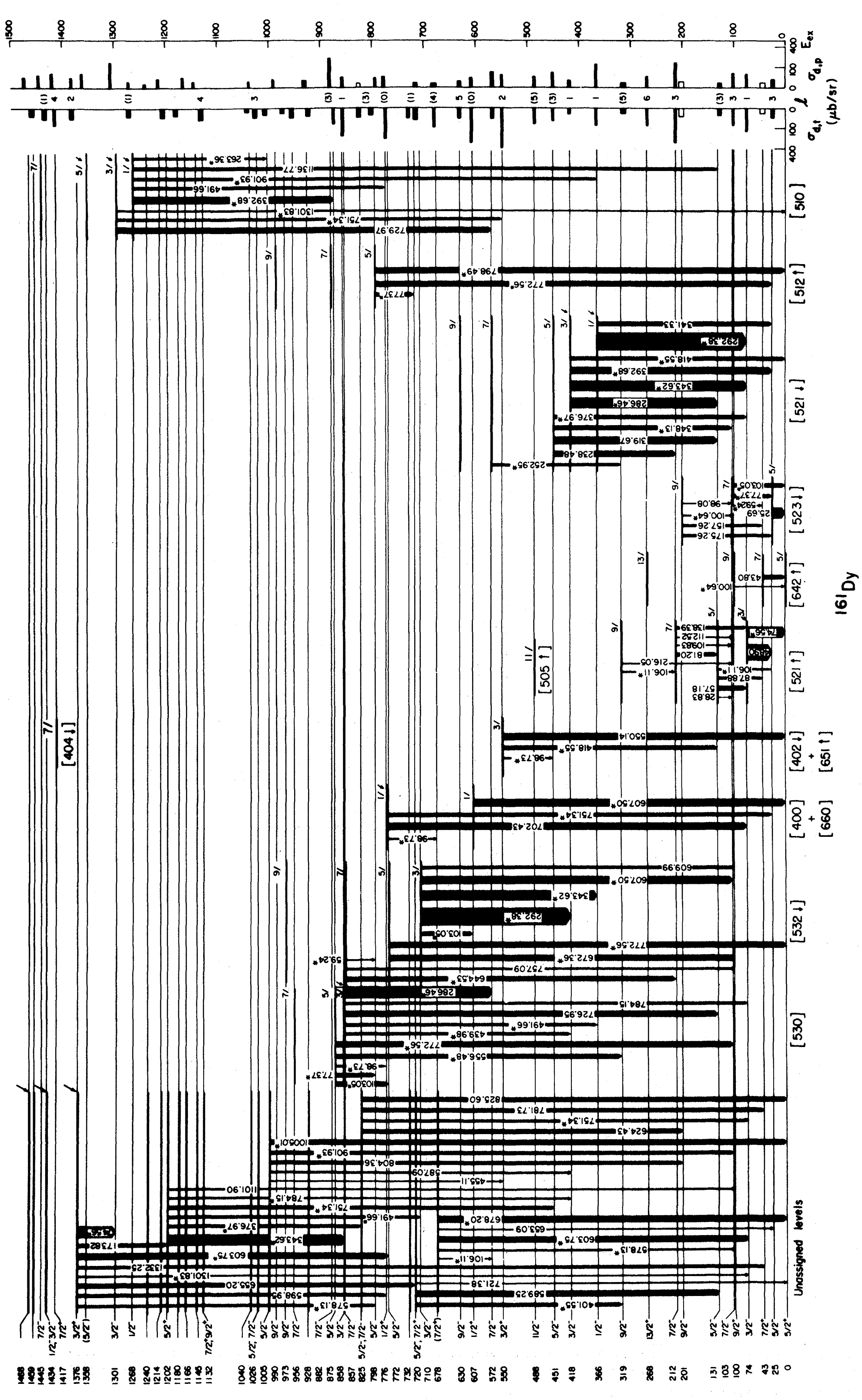

FIG. 6. Level scheme of ^{161}Dy. States are labeled in the left margin with their energies in keV and their assigned spin-parity values. The bar graphs on the right show the cross sections (on a square root scale) from the data of Fig. 1. The thickness of the bars indicates the error in the observed energies. The l value determined from the ^{162}Dy$(d,t)^{161}$Dy reaction at $E_d = 15$ MeV are shown between the bar graphs. Within the body of the level scheme states are arranged according to the Nilsson state assignments made in the text. The spin values for the states are shown at the right edge as, e.g., 9/ meaning $\frac{9}{2}$. A diagonal arrow to the right of the spin indicates direct (n,γ) population of the state from the capture state. The widths of the arrows designating γ rays are proportional to the square roots of the intensities. The asterisks denote either a multiple placement or a partial obscuration of the corresponding peak in the γ-ray spectrum by an impurity line.

TABLE IV. Rotational parameters for bands in ^{161}Dy.

Band	Energy (keV)	$\hbar^2/2\mathscr{I}$ (keV)	a	B (keV)
$\frac{5}{2}^+$[642]	0.0	6.22		0.002
$\frac{5}{2}^-$[523]	25.664	11.30		0.010
$\frac{3}{2}^-$[521]	74.562	11.27		0.014
$\frac{1}{2}^-$[521]	366.95	11.86	0.44	
$\frac{3}{2}^-$[532]	710.57	12.67		0.022
$\frac{5}{2}^-$[512]	798.22	11.92		−0.002
$\frac{1}{2}^-$[530] [a]	824.24	7.44	0.54	
$\frac{1}{2}^-$[510]	1268.58	11.15	−0.01	

[a] The rotational parameters for this band were calculated from the energies as the $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ members; as the bandhead is not observed, the energy shown is calculated with these rotational parameters.

information on the levels, namely, the level energy and its uncertainty, spin and parity, and Nilsson assignment. The states will be discussed by rotational bands in order of increasing excitation energy of the bandhead. Table IV presents a summary of the rotational parameters for the bands assigned. The parameters are those discussed in Ref. 2.

A. $\frac{5}{2}^+$[642] band

The ground state of ^{161}Dy has been measured to be $\frac{5}{2}^+$ and is assigned[2] as the bandhead of the $\frac{5}{2}^+$[642] rotational band. All members of this band up to $I^\pi = \frac{33}{2}^+$ have previously[3] been observed and identified.

In our (d,p) and (d,t) spectra, only the $\frac{7}{2}^+$ (44 keV) and $\frac{13}{2}^+$ (268 keV) rotational members are clearly resolved. The l value of the 268 keV state has been measured as 6, in agreement with the assignment. The peak in the direct reaction data corresponding to $E_{exc} \approx 100$ keV must be partly due to the $\frac{9}{2}^+$ member, but most of this peak appears to result from the state $\frac{7}{2}$, $\frac{5}{2}^-$[523], known to occur at 103.045 keV (see below). The observed cross section pattern for the $\frac{5}{2}^+$[642] band is in reasonable agreement with theory.[15]

The low-energy γ-ray data indicate energies of 43.825 and 100.42 keV for the above $\frac{7}{2}^+$ and $\frac{9}{2}^+$ members, in excellent agreement with the values 43.8 and 100.4 keV reported previously.[3] No evidence was found in the (n,γ) data for population of the $\frac{11}{2}^+$ and $\frac{13}{2}^+$ members.

B. $\frac{5}{2}^-$[523] band

The lowest-lying state observed in our direct reaction experiments is at an excitation energy of about 24 keV and has an angular distribution characteristic of $l=3$. This fact, together with the observed transition linking this state with the $\frac{1}{2}^-$[521] bandhead at 367 keV, requires the state to have spin-parity $\frac{5}{2}^-$. The γ-ray data show the energy of the state to be 25.664 keV. In agreement with the assignments quoted in Ref. 2, the state is assigned as $\frac{5}{2}$, $\frac{5}{2}^-$[523] by analogy with ^{163}Dy and ^{165}Er, in which it is the ground state. This assignment is also required by the observed logft (4.8) in the decay of ^{161}Ho.[16]

The state at 103.045 keV has previously been assigned as the $\frac{7}{2}^-$ band member.[1-3,6] Of the two peaks which make up the peaks observed at ≈100 keV in the (d,p) and (d,t) spectra, the one due to $\frac{7}{2}$, $\frac{5}{2}^-$[523] should be the strongest, consistent with the observed $l=3$ angular distribution of the doublet.

The $\frac{9}{2}^-$ band member is known to occur at 201 keV.[1-3,6] In our charged-particle spectra, this state is observed as a weak satellite peak on the high side of the 212 keV peak and thus its angular distribution could not be determined. The γ-ray data are consistent with the $\frac{9}{2}^-$ assignment and establish the state energy as 201.09 keV.

The $\frac{11}{2}^-$ member of this band, known to occur at 320.8 keV,[3] was not observed in these experiments but would have been obscured in the (d,p) and (d,t) spectra by the $\frac{9}{2}$, $\frac{3}{2}^-$[521] state at 319.16 keV.

The observed direct-reaction cross-section pattern for this band is consistent with the above assignments.

C. $\frac{3}{2}^-$[521] band

A state is observed at ≈74 keV in the direct reaction data which is more strongly populated by the (d,t) reaction than by (d,p) and thus has *hole* character. The angular distribution for the state is characterized as $l=1$. This state is also directly populated in the (n,γ) reaction. Thus, the state must have $I^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$. The low-energy γ-ray data determine the excitation energy of the state as 74.562 keV. The additional observation of a transition to the $\frac{5}{2}^+$ ground state requires that the spin and parity be $\frac{3}{2}^-$. Since the $\frac{3}{2}^-$[521] configuration is the ground state in ^{157}Dy and ^{159}Dy,[2] this same Nilsson assignment is made to the 75 keV state, as proposed in earlier studies.[1-3,6]

The (d,p) and (d,t) reactions both populate a *hole* state at approximately 126 keV whose angular distribution is consistent with $l=3$. The (n,γ) data indicate a state at 131.743 keV, in agreement with the value of 131.8 keV reported previously.[4] The

132 keV level is populated from the $\frac{1}{2}^-$ state at 1269 keV and the $\frac{3}{2}^+$ state at 550 keV and so must have spin and parity of $\frac{5}{2}^-$, consistent with the assignment $\frac{5}{2}, \frac{3}{2}^-[521]$ suggested previously.[1-3,6]

At 212 keV a state is observed with large cross section in both the (d,p) and (d,t) reactions. The (d,t) angular distribution of the state indicates $l=3$. The observed decay to the $\frac{9}{2}^+$ state at 100 keV limits the spin and parity assignment to $\frac{7}{2}^-$. The energy of the state is 212.94 keV, in agreement with the previously measured value.[2,3] The I^π value and the very large cross sections confirm the previous[1-3,6] $\frac{7}{2}, \frac{3}{2}^-[521]$ assignment.

The $\frac{9}{2}^-$ member of this band should be near 315 keV. Direct reaction peaks are observed at this energy with a probable angular momentum transfer of 5 units. In Ref. 3 it is suggested that the $\frac{9}{2}^-$ state is at 315.0 keV, but it is shown there as questionable. Also, the $\frac{11}{2}, \frac{5}{2}^-[523]$ state should be observed at approximately this energy. The present γ-ray data indicate a state at 319.16 keV which appears to be populated from the $\frac{5}{2}^-$ state at 875 keV and could not be $\frac{11}{2}^-$. In addition, the direct reaction cross sections of the 319 keV state are more in accord with the $\frac{9}{2}, \frac{3}{2}^-[521]$ assignment. It is quite possible that the direct reaction peaks seen here contain components of both of these states. We assign the 319 keV state as $\frac{9}{2}, \frac{3}{2}^-[521]$, in agreement with previous assignments.[1,6]

D. $\frac{1}{2}^-[521]$ band

A state at an excitation energy of 367 keV is observed strongly in the (d,p), (d,t), and high energy (n,γ) data and, in fact, is used as the excitation energy reference peak in all three cases. The (d,t) angular distribution of the state has $l=1$ shape, in agreement with the known spin and parity of $\frac{1}{2}^-$.[2] The energy of the state is seen to be 366.95 keV from the low-energy γ-ray data. The state is predominantly of *particle* nature, and it is therefore assigned as the head of the $\frac{1}{2}^-[521]$ band, as proposed previously.[1,2,6] There are also expected to be significant components in this state of the $|K-2|$ γ vibrational bands built on both the $\frac{5}{2}^-[523]$ and the $\frac{3}{2}^-[521]$ bands.[17]

The direct reaction data show a *particle* state at 419 keV. The (d,t) angular distribution indicates $l=1$. The excitation energy of the state is 418.19 keV, as determined by the low-energy (n,γ) data. The state is also seen in the high-energy (n,γ) data. The presence of a transition to the $\frac{5}{2}^+$ ground state, together with the measured l value, requires a spin and parity of $\frac{3}{2}^-$ for the state. It is therefore assigned as $\frac{3}{2}, \frac{1}{2}^-[521]$, in agreement with earlier work.[1,2,6]

A state at $E_{exc} \approx 450$ keV is seen in the (d,p) and (d,t) data. Its angular distribution is consistent with $l=3$, and the relative (d,p) and (d,t) cross sections indicate a *particle* nature. An excitation energy of 451.42 keV is deduced from the (n,γ) data. A 98.73 keV γ ray is seen which could populate the 451 keV level from the $\frac{3}{2}^+$ state at 550 keV. While this γ ray can be placed elsewhere in the level scheme (this possibility is discussed below), we believe that it is correctly placed here. Thus, a spin and parity of $\frac{5}{2}^-$ is proposed for the state, which is presumed to be the $\frac{5}{2}, \frac{1}{2}^-[521]$ rotational level. The values of the decoupling parameter ($a=0.440$) and the inertial parameter ($\hbar^2/2\mathcal{I}=11.86$ keV) agree with those measured in nearby nuclei ($a \simeq 0.4$ and $\hbar^2/2\mathcal{I} \simeq 12$ keV).[2]

The energy for the $\frac{7}{2}^-$ rotational state predicted with these parameters is 571 keV. There is a state observed near this energy in the (d,p) and (d,t) reactions. The excitation energy of this state is found to be 572.30 keV from the low-energy γ-ray data which are consistent with either $I^\pi = \frac{5}{2}^-$ or $\frac{7}{2}^-$. We conclude that the state is $\frac{7}{2}, \frac{1}{2}^-[521]$.

The (d,p) and (d,t) reactions indicate a *particle* state at 630 keV with $l=5$, which we assume to be the $\frac{9}{2}^-$ rotational level. No evidence for this state was found in the low-energy (n,γ) data. The direct reaction cross sections for the states at 367, 418, 451, 572, and 630 keV fit the expected pattern for the $\frac{1}{2}^-[521]$ band. The $\frac{11}{2}^-$ rotational state would be expected near 800 keV and a state is observed near that energy. Grotdal *et al.*[1] make this assignment. However, the (d,t) angular distribution for the state in question indicates that transferred $l=3$, and we have assigned the state to be $\frac{5}{2}, \frac{5}{2}^-[512]$. All of the members of the $\frac{1}{2}^-[512]$ band have been previously assigned.[1,2,6]

E. $\frac{11}{2}^-[505]$ band

At an excitation energy of 488 keV the direct reaction data show a *hole* state whose angular distribution suggests that it is of high spin ($l \approx 5$). Based on the tentative l value, the cross sections for populating the state, and its excitation energy, it is assigned as the $\frac{11}{2}^-[505]$ bandhead, in agreement with earlier assignments.[1,3] There is no consistent set of γ rays which appear to depopulate a state near this energy.

F. Mixed $\frac{3}{2}^+[402]$ and $\frac{3}{2}^+[651]$ bands

The (d,t) reaction strongly populates a *hole* state near 552 keV. The observed angular distribution is characteristic of $l=2$, so that $I^\pi = \frac{3}{2}^+$

or $\frac{5}{2}^+$. The low-energy γ-ray data are consistent with either spin and indicate an excitation energy of 550.17 keV. Based on the Nilsson diagram,[18] the most likely assignment is $\frac{3}{2}^+[651]$, but by analogy with the lowest $\frac{3}{2}^+$ states observed in other odd-neutron nuclei in this mass region,[2,7,19-21] a sizable admixture of $\frac{3}{2}^+[402]$ can be expected. An assignment as the pure $\frac{3}{2}^+[651]$ configuration can be ruled out by the very large (d, t) cross section for populating the state, since the model predicts that most of the strength of the $\frac{3}{2}^+[651]$ band should lie in the $\frac{13}{2}^+$ member. On the other hand, appreciable $\frac{3}{2}^+[651]$ character is indicated by the rather strong Coulomb excitation of this state from the $\frac{5}{2}^+[642]$ ground state.[22] In fact, if the maximum theoretical Coriolis coupling between the $\frac{3}{2}^+[651]$ state and the ground state is assumed, the measured $B(E2)$ of 1.2 spu (single-particle units)[22] represents a lower limit of approximately 40% of $\frac{3}{2}^+[651]$ in the wave function. Also, the presence of a sizable $\frac{3}{2}^+[402]$ component configuration is clearly indicated by the log*ft* value (6.0) of the β transition[23] from ^{161}Tb (β decay from $\frac{3}{2}^+[411]$ to $\frac{3}{2}^+[651]$ is strictly forbidden in the simple Nilsson model) and by the C_{jl} extracted from the (d, t) cross section for the state, which implies $\approx 60\%$ $\frac{3}{2}^+[402]$. Thus, all of our experimental evidence suggests that this state is best described as a mixture of approximately 40% $\frac{3}{2}^+[651]$ and 60% $\frac{3}{2}^+[402]$. This discussion has been presented previously.[2,6]

The complementary configuration, 60% $\frac{3}{2}^+[651]$ and 40% $\frac{3}{2}^+[402]$, is not assigned in the present work. Grotdal *et al.*[1] propose the *hole* state at 680 keV as the complementary mixed configuration. This assignment is supported by the (d, t) angular distribution analysis.[3] However, our (d, t) angular distribution suggests $l=4$ rather than $l=2$ (see Fig. 3). The low-energy γ-ray data determine the energy of the state as 678.35 keV. The 578.13 keV transition fits between the 678 keV level and the $\frac{9}{2}^+$ level at 100 keV. Therefore, we conclude that the 678 keV state cannot have $I^\pi = \frac{3}{2}^+$. A spin-parity of $\frac{7}{2}^+$ is consistent with all of the available data except for the possible placements of the 98.73 keV transition from the $\frac{1}{2}^+$ state at 777 keV and the 603.75 keV transition which we believe to be correctly placed elsewhere in the decay scheme.

Theoretical calculations suggest that the 550.17 keV state contains approximately 90% of the $\frac{3}{2}^+[402]$ strength, which would imply that the (d, t) cross section for the other mixed $\frac{3}{2}^+$ state should be quite small. This would be consistent with the fact that no other $l=2$ state is observed in this energy region. However, our experimental estimate of the mixing ratio of the 550 keV state predicts a somewhat larger cross section for the "missing" $\frac{3}{2}^+$ state. The higher spin members of these $\frac{3}{2}^+$ bands are usually so strongly mixed with other positive parity states that we would not expect to observe identifiable rotational bands in these experiments.

G. Mixed $\frac{1}{2}^+[400]$ and $\frac{1}{2}^+[660]$ bands

States at 607 and 777 keV are strongly populated in the (d, t) reaction, with angular distributions suggestive of $l=0$. The 777 keV state is also populated by a direct high-energy (n, γ) transition.

The evidence for these levels from the low-energy γ-ray data is somewhat ambiguous. The 607 keV level is apparently depopulated only by a strong transition to the ground state. It is possibly populated by a transition from the $I^\pi = \frac{3}{2}^-$ state at 710.57 keV, although this transition can be placed elsewhere in the decay scheme. The excitation energy of the state, as determined from these γ rays, is 607.51 keV. There are six low-energy γ-ray loops defining a level at 776.99 keV. Of these six γ rays, the placement of four must be considered as tentative since they can be assigned elsewhere in the decay scheme. The two γ rays that are uniquely placed, a 702.43 keV transition to the $\frac{3}{2}^-$ state at 74.56 keV and a 598.95 keV transition from the $\frac{3}{2}^+$ state at 1376.3 keV, are both consistent with a spin and parity of $\frac{1}{2}^+$ for the 776.99 keV state.

H. $\frac{3}{2}^-[532]$ band

Peaks are observed in both the (d, p) and (d, t) spectra near an excitation energy of 720 keV. The (d, p) data exhibit a single very weak peak at an excitation energy of 718 keV, and the (d, t) data exhibit a broad peak which, if analyzed as a doublet, has component energies of 716 and 732 keV. The angular distribution of the composite peak observed in the (d, t) reaction suggests $l=1$, but with considerable uncertainty. A fit with three components to the peak in the (d, t) data would also have been possible, but the difference between a two-component fit and a three-component fit was not statistically significant. Accordingly, the two-component fit was used and is given in the accompanying data tables. However, the low-energy γ-ray data suggest that there are, in fact, states at energies of 710.57 and 720.95 keV. Thus the $\approx$720 keV (d, t) peak is probably a triplet. If one fixes the two lower members at ≈ 711 and ≈ 721 keV, the upper member must be ≈ 735 keV in order to account for the observed peak shape. The peak at ≈ 711 keV appears to be the strongest component and should dominate the angular distribution. The 710.57 keV state can be fitted into six γ-ray loops, which implies a spin and parity of $\frac{3}{2}^-$, consistent with the l value. Although most of these γ rays can be fitted in elsewhere, the rms error in E_{exc} is only 0.02 keV and this lends confidence to the $\frac{3}{2}^-$ assignment. Based primarily on the energy of the state, we assign it as the bandhead of the $\frac{3}{2}^-[532]$ configuration, which should appear here as a *hole* state slightly below the $\frac{1}{2}^-[530]$ state.[2] This Nilsson state has been observed previously only in ^{153}Sm,[7] ^{159}Dy,[1] and ^{157}Dy,[1] where its inertial parameter ranges from 11.1 to 12.6 keV. Thus, the $\frac{5}{2}^-$ member of the band is expected to lie near 770 keV. The strong $l=0$ state at 777 keV would obscure the state in the (d,p) and (d,t) data, and so the low-energy γ-ray data offer the only possibility of observing it. Unfortunately, at this excitation energy the number of change combinations is becoming large (≈ 3 binary combinations per keV). Thus a state whose existence is established only by the combination principle must be considered questionable unless the loops have unusually small energy errors. A state is observed at 772.55 keV involving four γ-ray loops whose errors range from 0.09 to 0.21 keV. The γ rays can all be fitted into the level scheme at other places, but if their placement as connecting to this state is correct, then the spin and parity of the state could range from $\frac{3}{2}^{\pm}$ to $\frac{7}{2}^{+}$. We have made a tentative assignment of the 772.55 keV state as the $\frac{5}{2}^-$ rotational member of this band. This yields a value for $\hbar^2/2\mathscr{I}$ of 12.4 keV and predicts the $\frac{7}{2}^-$ member at ≈ 859 keV. Any state at this energy would be obscured in the direct reaction data by the $\frac{3}{2}$, $\frac{1}{2}^-[530]$ state at 858.69 keV. However, the low-energy γ-ray data suggest a tentative level at 857.50 which could have $I^{\pi}=\frac{5}{2}^{+}$, $\frac{7}{2}^{\pm}$, or $\frac{9}{2}^-$. We assign this state as the $\frac{7}{2}^-$ rotational member of the band. Again, we must emphasize the difficulties in making assignments on the basis of the combination principle at these energies.

The $\frac{9}{2}^-$ rotational state, predicted to be at 971 keV, is tentatively identified with the weak (d,t) state observed at ≈ 972 keV.

There are several other Nilsson states with *hole* character with which the $\frac{3}{2}^-[532]$ could Coriolis couple and so it is difficult to predict the cross sections for the various band members. Since the assignment for the band cannot be confirmed by the direct reaction cross section pattern and since the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ members are tentative levels based on the combination principle, the Nilsson assignment must be considered tentative.

I. $\frac{5}{2}^-[512]$ band

This Nilsson state should be recognizable in ^{161}Dy by a very large (d,p) cross section populating the $\frac{7}{2}^-$ rotational state at an excitation energy of about 900 keV, and a weaker $\frac{9}{2}^-$ state approximately 110 keV above.[2] Such states are observed at excitation energies of 882 and 990 keV, respectively, and have been previously assigned.[1,6] They are not seen in the (d,t) spectra and so the spin-parity assignments cannot be confirmed by angular momentum transfer assignments. Based upon the excitation energies of the $\frac{7}{2}^-$ and the $\frac{9}{2}^-$ states, the bandhead should be at an energy of ≈ 799 keV. The (d,p) reaction populates a state at 793 keV, while the (d,t) reaction shows a state at 803 keV with $l=3$. Although this is a separation of twice the combined errors, it is still possible that there is only one state, at an assumed excitation energy of 798 keV. The low-energy (n,γ) data indicate a state at 798.22 keV. A spin-parity assignment of $\frac{5}{2}^-$ for this state is favored by the 578.13 keV transition which may populate it from the $\frac{3}{2}^+$ state at 1376 keV and by the $l=3$ (d,t) angular distribution. We assign the 798 keV level as the bandhead of the $\frac{5}{2}^-[512]$ Nilsson state.

J. $\frac{1}{2}^-[530]$ band

A state at 854 ± 3 keV is strongly populated by the (d,t) reaction and is characterized as having an $l=1$ angular distribution. This state is also observed in the high-energy (n,γ) spectrum at an energy of 858.2 ± 0.6 keV. The low-energy γ-ray data yield a state energy of 858.69 ± 0.06 keV and are consistent with a spin and parity assignment of $\frac{3}{2}^-$. The $\frac{3}{2}^-$ member of the $\frac{1}{2}^-[530]$ band is expected to be seen in ^{161}Dy with a large (d,t) cross section at an energy slightly above the $\frac{3}{2}^-[532]$ state. There is no evidence in the present data for the $\frac{1}{2}^-$ bandhead of this configuration, which should occur at an excitation energy of ≈ 825 keV. There is a state seen at that energy but, as discussed below, it probably has spin and parity $\frac{5}{2}^-$ or $\frac{7}{2}^-$. The $\frac{5}{2}^-$ band member is predicted to be near 875 keV, based on the rotational parameters for the $\frac{1}{2}^-[530]$ band observed in ^{155}Gd.[2] There is a state observed at 871 keV in the (d,t) spectra of the present work. The (d,t) angular distribution suggests $l=3$. However, the $\frac{7}{2}$, $\frac{5}{2}^-[512]$ state is seen strongly in the (d,p) data at an energy of 883 keV and it is difficult to tell how much of the observed (d,t) cross section is due to this state. Both configurations, of course, would have $l=3$. The low-energy (n,γ) data show a $\frac{5}{2}^-$ state at 875.63 keV.

The (d,t) data show a level at 956 keV excitation which is assigned as the $\frac{7}{2}^-$ member of this band. The $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ members of this band have been previously assigned.[1]

K. $\frac{1}{2}^-$[510] band

The energy systematics of odd-neutron states[2] indicate that the $\frac{1}{2}^-$[510] Nilsson state should be seen at an excitation energy of ≈ 1300 keV in ^{161}Dy.

Our high energy (n, γ) data show a state at 1270 keV excitation, and peaks are observed at ≈ 1272 keV in the (d, p) and with $l=1$ in the (d, t) data. Also, a possibe state at 1268.58 keV is implied by the low-energy (n, γ) data. The decay of this state to the $\frac{1}{2}, \frac{1}{2}^-$[521] state at 367 keV, to the $\frac{5}{2}, \frac{3}{2}^-$[521] state at 131 keV, and to the $\frac{1}{2}^+$ state at 777 keV, together with the direct (n, γ) population, requires that the state have spin and parity $\frac{1}{2}^-$ or $\frac{3}{2}^\pm$. We assign it as the $\frac{1}{2}^-$[510] bandhead.

The high-energy (n, γ) data indicate a state at 1303 keV and the (d, p) reaction strongly populates a state at 1306 keV. The low-energy (n, γ) data suggest a level at 1301.69 keV whose spin and parity could be either $\frac{3}{2}^-$ or $\frac{5}{2}^\pm$. Thus, the combined data require $I^\pi = \frac{3}{2}^-$ and we assign the state as $\frac{3}{2}, \frac{1}{2}^-$[510], in agreement with Ref. 1.

States are also observed in the (d, p) data at excitation energies of 1361 and 1445 keV, which are tentatively assigned as the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ rotational states of the $\frac{1}{2}^-$[510] band. The rotational parameters for the band, given in Table IV, are in good agreement with those observed elsewhere.[2] The predicted C_{jl}'s for the $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ states agree well with the pattern observed. There is, however, a difficulty with the assignment of the 1362 keV state as the $\frac{5}{2}^-$ rotational member of the band. There is a strong primary line to a level having an energy of 1358 keV in the high-energy (n, γ) data. If this level corresponds to the above 1362 keV state, it would rule out the $\frac{5}{2}^-$ assignment. However, the impurity peak density due to other Dy isotopes at this energy in the high-energy (n, γ) data is quite high and, in addition, the level density at $E_{\text{exc}} \approx 1400$ keV in the ^{161}Dy nucleus is also high at this energy. Therefore, we have assumed that the state seen in the high-energy (n, γ) data is not the same one seen in the (d, p) reaction. The $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ members of the $\frac{1}{2}^-$[510] band have been previously assigned.[1]

L. $\frac{7}{2}^+$[404] band

A state at 1415 keV is strongly populated by the (d, t) reaction. The angular distribution of this state $(l=4)$ implies $I^\pi = \frac{7}{2}^+$ or $\frac{9}{2}^+$, in agreement with the assignment made by Grotdal *et al.*[1] of the state as the $\frac{7}{2}^+$[404] bandhead. The apparent strong (d, p) population may be due to some unknown mixing.

M. Other states

Several unassigned states are shown in Fig. 6 and in Table I. States for which information, in addition to (d, p) and (d, t) population, is available are discussed below. An exception is the state at 678.35 keV which is discussed in Sec. IV F.

The unassigned state at 720.95 keV is seen in the (d, p) reaction and, probably, in the (d, t) reaction. The low-energy (n, γ) data indicate that this state is populated both from the $\frac{3}{2}^+$ state at 1376 keV and the $\frac{5}{2}^-$[512] bandhead at 798 keV. The state decays to the $\frac{5}{2}^+$[642] ground state and to the $\frac{5}{2}^-$ and $\frac{9}{2}^-$ members of the $\frac{3}{2}^-$[521] band at 131 and 319 keV, respectively. This implies a spin and parity for the state of $\frac{5}{2}^-$ or $\frac{7}{2}^+$. This level might have been assigned as the $\frac{7}{2}^+$[633] bandhead, which is expected to appear here as a weak *particle* state between the $\frac{1}{2}^-$[521] and the $\frac{5}{2}^-$[512] states. However, the very weak ground-state transition is in conflict with such an assignment, as is the lack of observable (d, p) population of the $\frac{9}{2}^+$ and $\frac{13}{2}^+$ rotational band members.

Since the state observed at 823 ± 6 keV in the (d, t) data is not observably populated in the (d, p) reaction, we conclude that it is a *hole* state. The angular distribution is suggestive of $l=3$. The low-energy (n, γ) data yield an energy of 825.55 keV and indicate four possible decay modes for the state, as well as population from the $\frac{5}{2}^+$ state at 1202 keV, all of which suggests that $I^\pi = \frac{5}{2}^-$ or $\frac{7}{2}^-$, in agreement with the tentative l value.

The (d, t) data indicate a level at 1206 keV for which no l-value assignment can be made. The low-energy (n, γ) data indicate a state at 1202.35 with $I^\pi = \frac{5}{2}^+$. There are eight γ-ray placements associated with this state; however, most of these are duplicate placements and so the spin-parity assignment for the state is tentative.

A level is observed in the (d, p), (d, t), and high energy (n, γ) data at an excitation energy of approximately 1380 keV. The $l=2$ angular distribution of the state, together with the direct (n, γ) population, requires a spin and parity of $\frac{3}{2}^+$. The low-energy (n, γ) data would require the same I^π assignment and yield an excitation energy for the state of 1376.18 keV. Both (d, p) and (d, t) population of a state at this energy could imply a vibrational assignment. However, the observed cross sections are too large for any reasonable vibrational assignment. The observed decay modes

TABLE V. Comparison of energies of configuration in ^{161}Dy and ^{163}Er with calculations.

K^{π}	^{163}Er [a]	^{161}Dy	Calc. [b]	Structure
$\frac{5}{2}^-$	0	26	0	523↓ 96%
$\frac{5}{2}^+$	69	0	−10	642↑ 97%
$\frac{3}{2}^-$	104	75	75	521↑ 95%
$\frac{3}{2}^+$	463	550	260	651↑ 78%; 651↑+Q_1(20) 10%; 521↑+Q_1(30) 4%
$\frac{11}{2}^-$	444	488	280	505↑ 95%; 505↑+Q_1(20) 4%
$\frac{1}{2}^-$	346	367	480	521↓ 55%; 523↓+Q_1(22) 26%; 521↑+Q_1(22) 16%
$\frac{1}{2}^+$	541	608	500	660↑ 65%; 660↑+Q_1(20) 13%; 651+Q_1(22) 9%
$\frac{3}{2}^-$		711	500	532↓ 79%; 532↓+Q_1(20) 6%; 530↑+Q_1(22) 5%
$\frac{7}{2}^+$			680	633↑ 95%
$\frac{5}{2}^-$	609	798	930	512↑ 48%; 642↑+Q_1(30) 47%; 510↑+Q_1(22) 3%
$\frac{7}{2}^-$			980	523↑ 1%; 521↑+Q_1(22) 98%
$\frac{1}{2}^+$		777	1000	660↑ 3%; 640↑1%; 642↑+Q_1(22) 85%
$\frac{1}{2}^-$			1000	521↑+Q_1(22)60%; 523↓+Q_1(22) 35%
$\frac{9}{2}^+$			1000	624↑ 1%; 624↑ +Q_1(22) 98%
$\frac{9}{2}^-$			1050	523↓ +Q_1(22) ~ 100%
$\frac{3}{2}^+$			1200	651↑ 2%; 521↑+Q_1(30) 72%; 651↑+Q_1(20) 3%
$\frac{1}{2}^-$			1400	521↓ 40%; 523↓+Q_1(22) 35%; 521↑+Q_1(22) 13%
$\frac{1}{2}^-$	1074	1269	···	Expt: 510↑ 40%; 512↑+Q_1(22) 60%

[a] ^{163}Er data from Ref. 24.

[b] Calculations from Ref. 17.

seem to offer no clue as to the character of the state.

N. Comparison of the levels in ^{161}Dy and ^{163}Er with calculations

Table V presents a comparison of the levels calculated by Soloviev, Vogel, and Jungklaussen[17] specifically for ^{163}Er with those experimentally observed in ^{161}Dy and ^{163}Er.[24] It is interesting to note that the calculations, although made specifically for ^{163}Er, actually agree somewhat better with our experimental results on the isotone ^{161}Dy. In particular, the ground state and first excited intrinsic Nilsson configuration are $\frac{5}{2}^+[642]$ and $\frac{5}{2}^-[523]$ in ^{161}Dy, as calculated by Soloviev, whereas they are reversed in ^{163}Er. The lack of agreement between calculation and experiment for the $K^{\pi}=\frac{3}{2}^+$ and $\frac{1}{2}^+$ states is probably due in part to the fact that the calculations do not include the effects of $\Delta N=2$ coupling which this research and other work show[2,7,19-21] to be very significant.

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