Excited States of Dy^{161}

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The γ rays following β decay of Tb^{161} have been investigated with sodium iodide scintillation counters and with a xenon counter used with and without x-ray escape gating. Gamma rays of 74, 57, 49, and 26 kev were observed together with Dy x-rays. From these data and γ, K x-ray coincidence measurements, rough estimates are obtained for the K conversion coefficients of the 74- and 57-kev transitions. Combination of the γ-ray intensities with conversion-electron intensities determined by Cork, Brice, Schmid, and Helmer yields K and L conversion coefficients for all the transitions once the normalization of conversion electron and γ-ray intensities has been assumed. Where comparison is possible these conversion coefficients agree with those determined from the x-ray and γ-ray measurements alone.

The multipolarities seem largely compatible with the unified-model predictions of Nilsson. There is a possibility of at least one highly retarded $E1$ transition.

INTRODUCTION

THE most recent data on the β decay of Tb^{161} come from the conversion-electron studies of Cork, Schmid, Brice, and Helmer[1] and of Smith, Robinson, and Langer.[2] The findings of these two groups are shown in Fig. 1. They differ over the weak transitions and on the multipolarities of some strong ones. They are not inconsistent with the previous less complete investigations.[3]

This investigation attempts to confirm the decay scheme by coincidence measurements and to resolve the multipolarity questions by measurement of conversion coefficients. No values will be given for γ energies because the conversion electron work should be more accurate.

SOURCES

For all the experiments natural Gd_2O_3 was irradiated with pile neutrons by the Harwell Isotope department. The activities produced are 18-hr Gd^{159} [4] 7-day Tb^{161},[5] and 236-day Gd^{153}.[6] No chemical separation was performed; instead the various activities were distinguished by their different half-lives.

EXPERIMENTAL PROCEDURE AND RESULTS

The γ spectra were taken with a 1-in. cube NaI scintillation counter and a proportional counter of 2-in. diameter filled with 70 cm of xenon and 5 cm of ethylene. A typical scintillation spectrum is shown in Fig. 2, with the peaks identified.

The resolution obtained with the scintillator is insufficient to resolve the peak near 50 kv into its components but this is easily accomplished by the xenon counter if the xenon K x-ray escape peaks rather than the full energy peaks are employed. If, further, the full energy peaks are suppressed by the method of K escape gating,[7] the result is Fig. 3 which shows the γ's at 74, 57, and 49 kev. Figure 4, which compares spectra taken with and without suppression of full energy peaks, shows the 25-kev γ as a full energy peak.

Coincidence experiments between the scintillator and the xenon counter (again using the escape peaks where necessary) confirmed the decay schemes of Cork *et al.* and Smith *et al.*, but of course said nothing about the order of 25–49 kev cascade or the 57–74 kev cascade.

Intensity measurements were made by using both the scintillator and the proportional counter. As the efficiency of the scintillator is not very energy-dependent, and as what energy dependence there is is easily calculated, it was used in this study for comparisons involving large energy ratios. The scintillator records all the K x-rays and the 49- and 57-kev γ's as one broad peak which was apportioned among its components with the xenon counter. In this way the xenon counter was used for intensity comparison over a small range of energies only, so, even though its efficiency is highly energy-dependent, the errors introduced by faulty prediction of the energy dependence will be small. The data for calculating the scintillation-counter efficiency was taken from Bell's article in *Beta and Gamma Spectroscopy*.[8] Contributions from Gd^{153} were subtracted from the observed spectra where necessary.

The γ intensities normalized to give $I_\gamma(49)=1$ are shown in Table I and should be good to within about 15% except for the 25-kev γ ray for which the corrections are larger and 30% seems a safer limit.

The upper limits for the intensities of the 27.7- and 78-kev γ rays (which have been reported by Cork

[1] Cork, Brice, Schmid, and Helmer, Phys. Rev. **104**, 481 (1956).
[2] Smith, Hamilton, Robinson, and Langer, Phys. Rev. **104**, 1020 (1956).
[3] Scharff-Goldhaber, der Mateosian, McKeown, and Sunyar, Phys. Rev. **78**, 325(A) (1950); Cork, Le Blanc, Nester, and Stumpf, Phys. Rev. **88**, 685 (1952); H. Jaffe, University of California Radiation Laboratory Report UCRL-2537, 1954 (unpublished); R. Barloutaud, and R. Ballini, Compt. rend. **241**, 389 (1955); Bisi, Terrani, and Zappa, Nuclear Phys. **1**, 425 (1956).
[4] R. Ballini and R. Barloutaud, J. phys. radium **17**, 543 (1956).
[5] Jordan, Cork, and Burson, Phys. Rev. **92**, 315 (1953).
[6] R. E. Hein and A. F. Voight, Phys. Rev. **79**, 783 (1950).
[7] C. W. McCutchen, Nuclear Phys. **3**, 76 (1957).
[8] P. R. Bell, in *Beta and Gamma Spectroscopy*, edited by Kai Siegbahn (North Holland Publishing Company, Amsterdam, 1955).

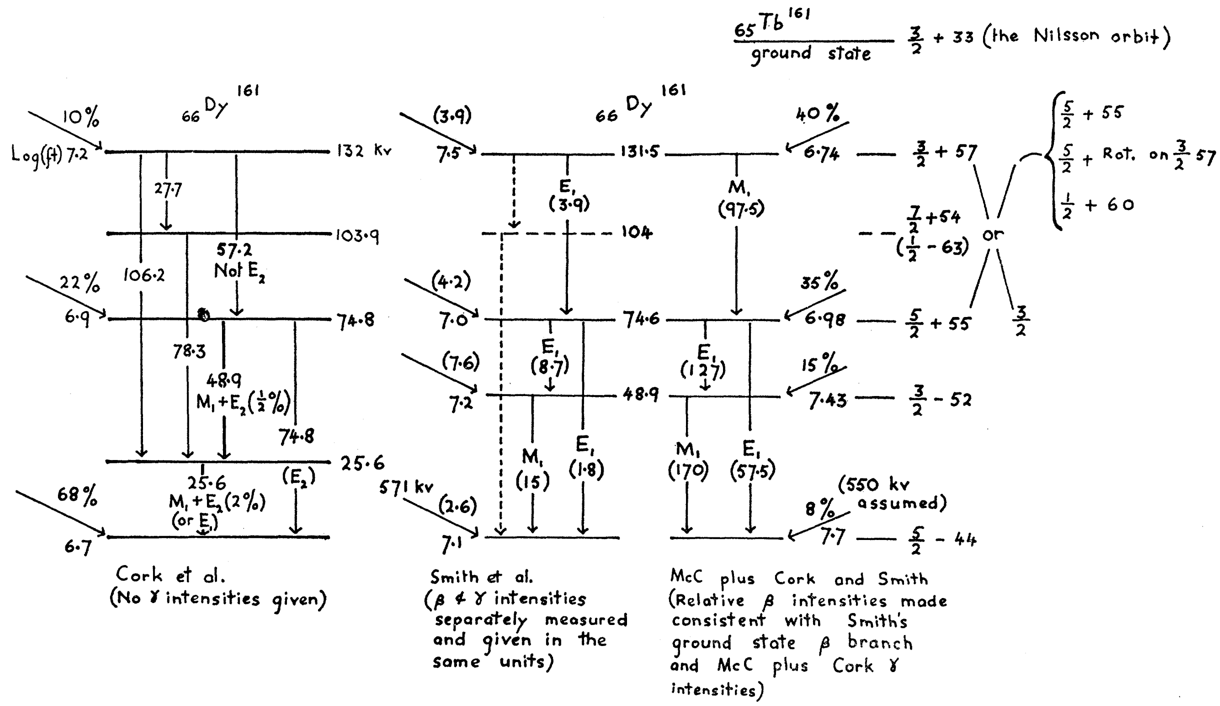

FIG. 1. Comparison of Tb^{161} decay schemes.

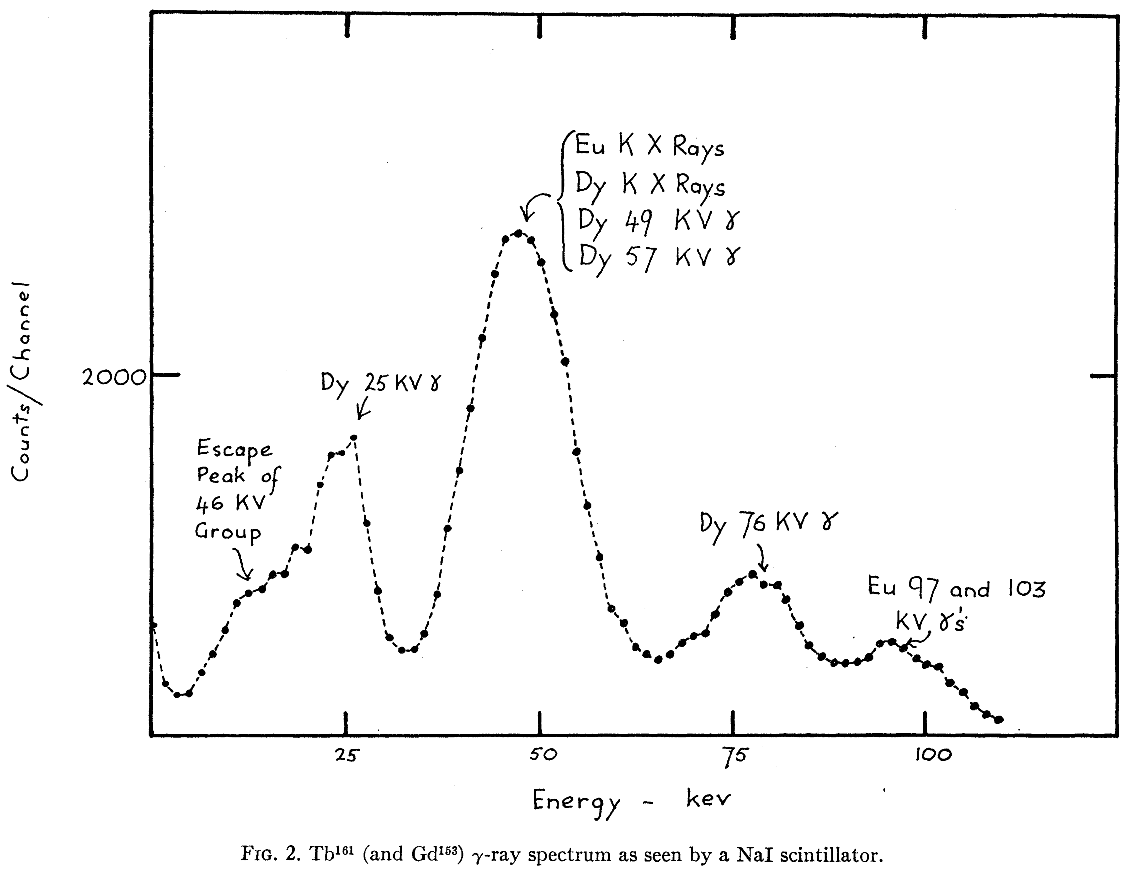

FIG. 2. Tb^{161} (and Gd^{153}) γ-ray spectrum as seen by a NaI scintillator.

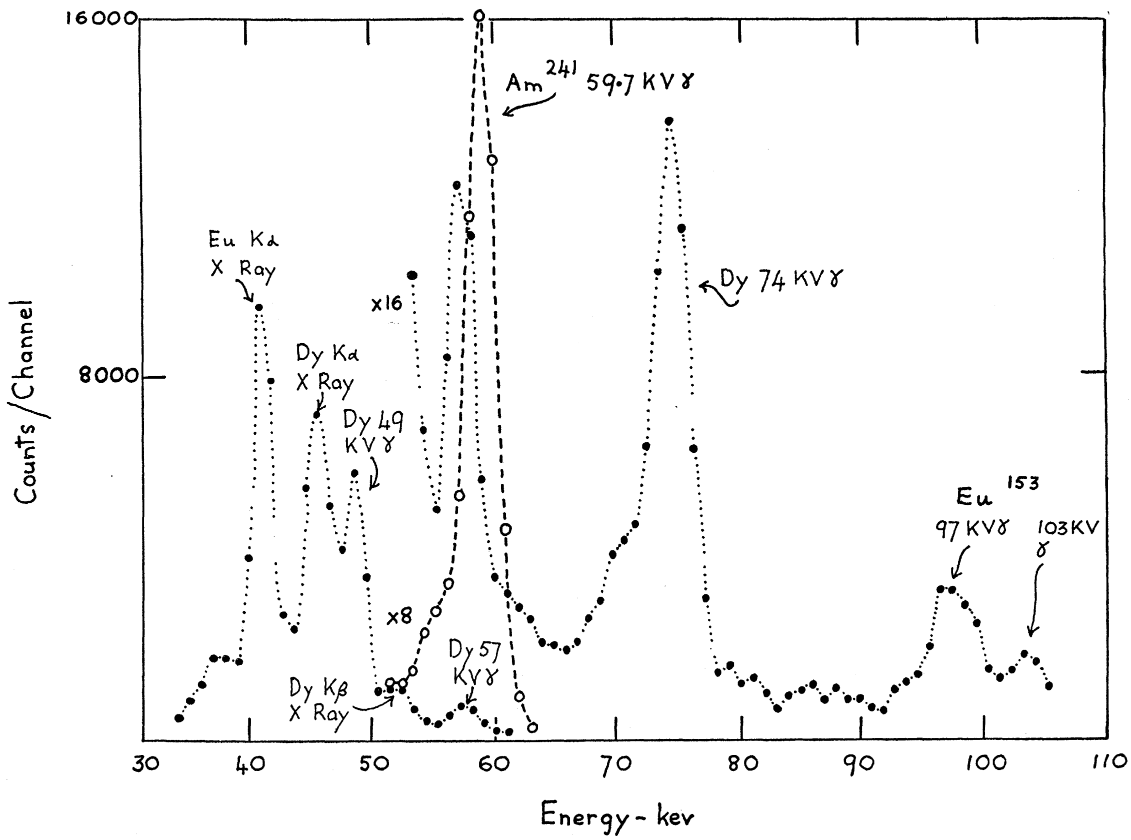

FIG. 3. Tb^{161} (and Gd^{153}) γ-ray spectrum as seen by the escape-gated xenon proportional counter.

et al.) were derived from the xenon counter spectra and are quite high because neither of these lines would be completely resolved from its intense neighbor. Coincidence experiments failed to reveal either one so, if the decay scheme of Cork *et al.* is correct, they are certainly very weak.

TRANSITION ORDER FROM γ AND X-RAY DATA ALONE

If all the x-rays were associated with the 57-kev transition, then $I_\gamma(57)+I(K_\alpha x)/0.74=2.06$ is the strength of the 57-kev transition (if we ignore γ's converted in the higher atomic shells). The "0.74" is the K_α fluorescence yield[9] for Dy. We know that $I_\gamma(25)+I_\gamma(74)=1.9$. Even for an $E1$ transition the total L conversion coefficient at 25 kev and $Z=63$ is about 2,[10] which makes $I_{\text{total}}(25)+I_{\text{total}}(74)=3.6$. This means that the 25- and 74-kev transitions cannot lie above the 57-kev transition in the decay scheme, and, of course, implies a β branch to what we now realize must be a level at 74 kev above the ground state. The second excited state is therefore at 74 kev. Note that when conversion of the 74-kev transition is considered the argument for the decay sequence becomes stronger. Nothing can be said about the order of the 25- and 49-kev transitions because as my counter cannot see L x-rays nothing certain can be learned about the relative total transition intensities.

CONVERSION COEFFICIENTS AND THE MULTIPOLARITY ASSIGNMENTS FROM THE γ AND X-RAY MEASUREMENTS

By taking spectra in coincidence with the 74-kev γ, the 57-kev transitions can be isolated and the ratio

$$I(K_\alpha \text{ x associated with 57-kev } \gamma)/I_\gamma(57)$$

measured. The K conversion coefficient is given by

$$I(K_\alpha \text{ x associated with 57-kev } \gamma)/\{[I_\gamma(57)][0.74]\},$$

TABLE I. Observed γ-ray intensities. The γ-ray energies are given in kev.

$I_\gamma(132)<0.007$	$I_\gamma(49)=1.0$
$I_\gamma(106)<0.02$	$I_\gamma(28)<0.18$
$I_\gamma(78)<0.19$	$I_\gamma(26)=0.89$
$I_\gamma(74)=0.935$	$I(K_\alpha x)=1.37$
$I_\gamma(57)=0.213$	

[9] This was obtained from a value (0.915) for the K fluorescence yield interpolated from the data tabulated by Broyles, Thomas, and Haynes [Phys. Rev. **89**, 715 (1953)] combined with an experimental determination, which I made on Eu, of the ratio of K_β to the K_α intensity. The result obtained was $I(\text{Eu } K_\beta)/I(\text{Eu } K_\alpha)=0.24$.

[10] Conversion coefficients used in this article were taken from the privately circulated tabulation of Rose, Goertzel, and Swift.

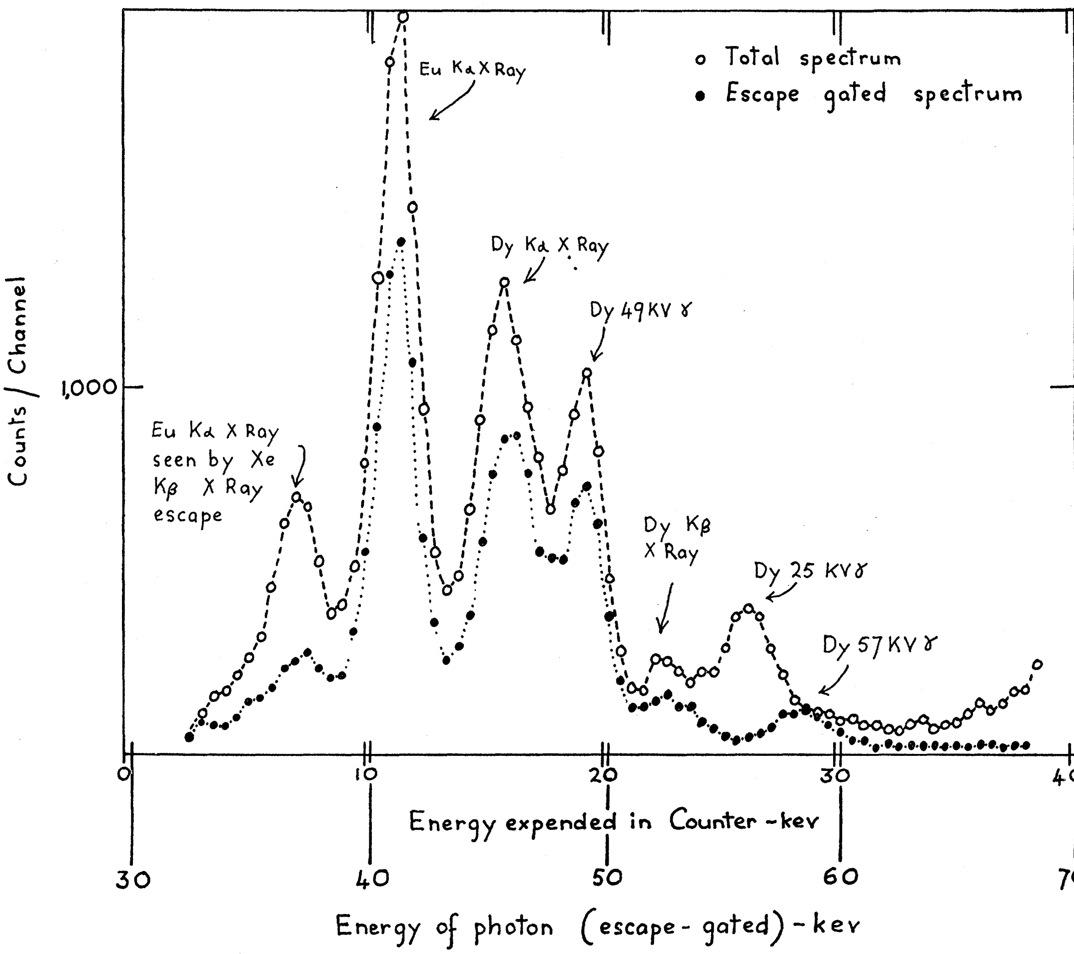

FIG. 4. Xenon counter spectra with and without escape-gating showing 25-kev γ ray as a full energy peak.

where the 0.74 is the K_α fluorescence yield. The result, in poor statistics, was

$$\alpha_K(57) = 8_{-3}^{+5},$$

which indicates either an $M1$ or $E2$ transition.

Combining this inaccurate result with the singles intensities, we find $\alpha_K(74) = 0.145$. This involves a subtraction and is extremely imprecise; however, a very definite upper limit can be set on $\alpha_K(74)$ by assuming that all the x-rays are associated with the 74-kev transitions. This yields

$$\alpha_K(74) < 0.62,$$

which definitely identifies the transitions as $E1$. The theoretical value for an $E1$ transition is 0.486 while the next lowest conversion coefficient, that for an $E2$ transition, is 2.1.

COMBINATION WITH THE CONVERSION-ELECTRON DATA OF CORK *et al.* MORE CONVERSION COEFFICIENTS

Dr. Cork has very kindly provided me with the intensities of conversion lines in the Tb^{161} spectrum. These are shown in Table II. The fairly similar values given by Smith *et al.* are included for comparison though they were not used in the computations. A direct normalization of γ and the conversion-electron intensities is not possible in this case because the electron spectroscopists do not see the K line from the 57-kev transition. If they did, comparison of the sum of the K lines with the K x-rays seen in the present work would provide the normalization.

Instead, the very likely assumption is made that since, from the γ and x-ray data of this investigation, the 74-kev γ is $E1$ the 25- and 49-kev γ's must be $E1$ and $M1$ respectively or vice versa. Further, since the 25- and 49-kev γ's are about equally converted $(I_e(25)/I_e(74) \cong I_\gamma(25)/I_\gamma(74))$ the 49-kev γ must be $M1$ and the 25-kev γ must be $E1$. We take the 49-kev transition to be $M1$ and adjust the normalization to agree with the theoretical L_1 conversion coefficient. This gives the values shown in Table III where they are compared with the theoretical values.

$\alpha_K(57)$ in this tabulation was obtained from the experimental value of $I(K_\alpha\,x)/I_\gamma(57)$ in the singles spectrum by subtracting the K x-rays, which Table II says were associated with the 74-kev transition.

The K conversion coefficients for the 57- and 74-kev transitions obtained from this trial normalization agree with the values obtained from the γ and K x-ray intensities alone even to the very low value for $\alpha_K(74)$. Except for this, all the conversion coefficients seem to agree entirely with the assumed multipolarities of the transitions. The assignments are shown in Fig. 1.

$\alpha_K(74)$ is 3 times less than the theoretical value for an $E1$ transition; this is surprising as the 74-kev γ peak is well resolved in my spectra and so is the 74-kev K line in the conversion-electron spectra. A normalization which makes this coefficient agree with the theoretical $E1$ value would, on the basis of the L_1 coefficient, make the 25- and 49-kev transitions $E2$ and $E3$ respectively, both of which assignments imply strong L_3 conversion which is not observed.

Note that had the conversion-electron data of Smith *et al.* been used instead of those of Cork *et al.*, the conversion coefficient of the 74-kev transition would have been very slightly lower still.

These multipolarity assignments agree with those of Smith *et al.* except in the case of the 57-kev transition which they find, by less direct arguments, to be $E1$. With this normalization of γ and conversion-electron intensities the total transition intensities were calculated. These are shown in Fig. 1. They fix the first excited state at 49 kev but the evidence is not very strong. This conclusion is in contradiction with the systematics of the weak transitions which Cork *et al.* observe and which Smith *et al.* do not.

β BRANCHING RATIOS AND *ft* VALUES

No β spectroscopy was performed. Instead, the β branching ratios were inferred from the total transition

TABLE II. Conversion electron and γ-ray intensities[a] in Tb^{161} β decay.

Line (E in kev)		Conversion electrons Cork	Total for transition	Smith	Total for transition	γ rays McCutchen
	L_1	36	86	19		
	L_2	27		14.3		41.5
25	L_3	23		21.5	75.2	
	M			18		
	N			2.4		
	L_1	100		100		
	L_2	16		Very small		47
49	L_3	7	123	Very small	134	
	M			25		
	N			9.5		
	L_1	12				10
	L_3	3				
57	M			1.2		
	N					
	K	8		7		
74	L_1	4	14		9.2	43.5
	L_3	2		1.2		

[a] The γ intensities are normalized as described in the text.

TABLE III. Internal conversion coefficients.

Transition energy (kev)		Experimental				Theoretical for $Z=65$
			α_1	β_2		
25.4	L_1	0.87	0.65	1129		
	L_2	0.65	0.446	74		at 25.5 kev
	L_3	0.555	0.68	565		
			α_2	β_1		
49	L_1	2.1	0.38	1.91		
	L_2	0.34	12.3	0.157		at 51.1 kev
	L_3	0.16	14.5	0.025		
			α_2	β_1	α_3	
57	K	7.25	3.5	8.3	9.5	
	L_1	1.2	0.32	1.42	5.0	at 57 kev by interpolation or extrapolation
	L_3	0.3	9.0	0.0175	350	
			α_1	β_2		
74	K	0.184	0.5	43		
	L_1	0.092	0.05	9.7		at 76.7 kev
	L_3	0.046	0.017	2.4		

intensities. The strength of the β branch to the ground state is taken from Smith *et al.* who inferred it from the ratio of total number of β decays to the number of γ transitions to the ground state. The results, assuming a β end point of 550 kev, are shown in Fig. 1. Log *ft* values were computed with the help of Moszkowski's nomograph.[11]

INTERPRETATION

The Nilsson[12] level scheme for deformed nuclei predicts that the ground state of Tb^{161} should be the $\frac{3}{2}+$ orbit 33. Tb^{159}, another 65-proton nucleus, has been found by Baker and Bleaney[13] to have spin $\frac{3}{2}$ so the assignment appears sound.

The ground state of Dy^{161} has been observed by Cooke and Park[14] to have spin $\frac{5}{2}$. The Nilsson scheme predicts either the $\frac{5}{2}+$ orbit 55 or the $\frac{5}{2}-$ orbit 44; the levels lie close together and cross quite near the likely deformation.

The Alaga selection rules[15] classify a β transition from orbit 33 to orbit 44 as first forbidden hindered and one from orbit 33 to orbit 55 as allowed hindered. The observed log *ft* value decides in favor of orbit 44. This agrees with the conclusions of Alaga for the analogous β transition (same neutron number—$^{\beta}\rightarrow$ same proton number):

$$_{64}Gd_{95}{}^{159}\xrightarrow{\beta^-}{}_{65}Tb_{94}{}^{159}.$$

For the first excited state, only the $\frac{3}{2}-$ orbit 52 satisfies the β and γ selection rules.

The β branch to the second excited state has log $ft=7$ which, according to Alaga, should make it first for-

[11] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).
[12] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, 16 (1955); B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).
[13] J. M. Baker and B. Bleaney, Proc. Phys. Soc. (London) **A68**, 257 (1955).
[14] A. H. Cooke and G. Park, Proc. Phys. Soc. (London) **A69**, 282 (1956).
[15] G. Alaga, Phys. Rev. **100**, 432 (1955).

bidden unhindered which it cannot be since this state decays to the ground state by $E1$ radiation. A slight constretch of the classification makes it allowed hindered and permits the assignment of the $\frac{5}{2}+$ orbit 55 or the $\frac{3}{2}+$ orbit 57, to either of which the β decay is allowed hindered.

The state at 132 kev can be the $\frac{5}{2}+$ orbit 55 or the $\frac{3}{2}+$ orbit 57 depending upon which is chosen as the 74-kev level. If the 74-kev level is $\frac{3}{2}+$, the assignment of the $\frac{1}{2}+$ orbit 60 is also possible for the 132-kev level.

This situation is summarized in Fig. 1 along with the possibility that the 132-kev level is a $\frac{5}{2}+$ rotational level being the first excited member of a rotational band built upon the $\frac{3}{2}+$ particle excited state at 74 kev.

Note that of all possible assignments for the 132-kev state ($\frac{7}{2}+$ would be fed by a second forbidden β decay) only $\frac{1}{2}+$ cannot decay to the ground state by $E1$ radiation. No one has seen this transition. $E1$ transitions in deformed nuclei are known to be retarded by large factors compared to the single-particle estimates (Strominger and Rasmussen[16]) but the factor required in this case to provide the necessary invisibility is about 4×10^6 which is a factor of 10 higher than any retardation yet found.

On this basis the $\frac{1}{2}+$ assignment is preferred; however, the level scheme then does not include the $\frac{5}{2}+$ orbit 55 which, according to the Nilsson diagram should appear at low excitation and which should attract an allowed β decay.

Little is certain about the 104-kev level except that the β decay to it is weak and that the 28-kev γ leading to it from the 132-kev level is observed by the conversion-electron spectroscopists. Two possible assignments are shown in Fig. 1.

If the intensity arguments are wrong (and they would not have to be far wrong) and the first excited state is at 26 kev, then the β and γ selection rules require one of the following sequences. Starting at the ground state and ignoring the 104-kev level, they are: $\frac{5}{2}-$ orbit 44, $\frac{5}{2}+$ orbit 55, $\frac{3}{2}+$ orbit 57, $\frac{1}{2}+$ orbit 60, $\frac{5}{2}-$ orbit 44, $\frac{7}{2}+$ orbit 54, $\frac{5}{2}+$ orbit 55, $\frac{3}{2}+$ orbit 57. The first sequence should have an allowed β branch to the first excited state and it is doubtful if the intensity measurements were that wrong. The second again requires great retardation of the $E1$ transition from the 132-kev level to the ground state. Both sequences have the 74-kev $E1$ transitions beaten by the competing 49-kev $M1$ transition but here the retardation factor is only 7×10^5.

These schemes at least have the virtue of including the $\frac{5}{2}-$ orbit 55.

CONCLUSION

The excited states of Dy^{161} can be fitted by the Nilsson level scheme, though not without a few difficult points. These schemes might all be upset if the ground-state β branch were found to be much stronger (as Cork *et al.* believe), for the ground-state β transition might then be allowed and require a different assignment for the ground state.

The very low K conversion coefficient for the 74-kev $E1$ transition is an unresolved mystery.

[16] D. Strominger and J. O. Rasmussen, Nuclear Phys. **3**, 197 (1957).