Decay of $_{66}Dy^{166}$†

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(Received March 10, 1960)

Samples of Dy^{166} were produced by successive neutron capture in stable Dy^{164}. This isotope decays by beta-ray emission with an 80.2-hr half-life to states in Ho^{166}. This isotopic assignment of previous authors is confirmed. Separations of the parent and daughter activities were carried out by use of an ion-exchange column. Scintillation studies were made with a 256-channel scintillation coincidence spectrometer. Internal-conversion electrons were measured in magnetic spectrographs with permanent magnets and the continuous beta spectra were observed with a 180° magnetic spectrometer with a variable field. The seven gamma-ray transitions observed had energies of 28.1, 54.2, 82.5, 288, 344, 375, and 428 kev. Beta-ray branches of 481 and 402 kev were observed with the magnetic spectrometer; two others of 114 and 56 kev are postulated for the decay scheme. The decay scheme presented indicates the existence of five levels in $_{67}Ho^{166}$ at $0(0^-)$, $54(2^-)$, $82(1^-)$, 370, and $428(1^+)$ kev. The ground state and first two excited states are interpreted as members of a rotational band with $K=0$. This interpretation implies that in odd-odd nuclei the level sequence can be inverted for the first two excited states of such a band.

INTRODUCTION

An 81-hr β^- activity was reported in samples of dysprosium that had been irradiated with neutrons.[1,2] Ketelle, using sources separated in an ion-exchange column, found that this activity was associated with the precursor of a daughter exhibiting a period of 27 hr. For the latter activity, both the half-life and the end-point energy of the beta spectrum (measured by aluminum absorption methods) agreed with those reported for the 27-hr activity of Ho^{166}. The 81-hr activity was therefore assigned to Dy^{166}, which would be produced by double neutron capture. Using a chemically separated sample of Dy^{166}, Ketelle found the end point of the beta spectrum to be 0.4 Mev. The neutron-capture cross section in Dy^{165} was estimated to be 5000 barns.

Independently, Butement investigated this activity and arrived at the same assignment. Butement also found that the yield of the 81-hr activity was approximately proportional to the square of the neutron flux. In addition, he found that the neutron capture in Dy^{165} takes place mainly, if not entirely, in the 2.3-hr ground state. Using an unseparated dysprosium source, he found the end point of the Dy^{166} beta spectrum (by aluminum absorption methods) to be 0.22 Mev. By the usual technique of absorption measurements in aluminum, copper, and lead, some low-energy (less than 50-kev) gamma radiation was found in Dy^{166}.

Relationship of Activities

From the above information, the activities of interest in this study were presumed to be related as follows:

$$\begin{array}{ccccc} Dy^{164} & \xrightarrow{(n,\gamma)} & Dy^{165} & \xrightarrow{(n,\gamma)} & Dy^{166} \\ & & \beta^-\downarrow (2.3\text{ hr}) & & \beta^-\downarrow (80\text{ hr}) \\ & & Ho^{165} & \xrightarrow{(n,\gamma)} & Ho^{166} \\ & & & & \beta^-\downarrow (27\text{ hr}) \\ & & & & Er^{166}. \end{array} \quad (1)$$

For simplicity and because of the results of Butement, the 1.2-min isomeric state of Dy^{165} has been omitted from this diagram. In this report references to Ho^{166}, except where otherwise noted, refer to the 27-hr ground state; the long-lived isomer (half-life $\gtrsim 30$ hr) was not observed. The conclusions of the previous authors concerning the isotopic assignments of the various related activities are confirmed by this study. Discussion of this evidence is deferred until all of the experimental data have been presented since many of the results bear indirectly upon this issue.

Apparatus

In this investigation, an Argonne 256-channel scintillation coincidence spectrometer was used. The gamma-ray detectors are $2\frac{1}{4}$-in. cubic NaI(Tl) crystals; an anthracene crystal $\frac{3}{16}$ in. thick by $1\frac{1}{2}$ in. in diameter is used as a beta-ray detector. In order to be able to detect low-energy beta rays, the light shield on the latter crystal is constructed so that the source can be placed next to the crystal with no intervening absorbers. For coincidence experiments, a single-channel pulse-height analyzer and "fast-slow" coincidence circuit ($2\tau=40$ mμsec) are used to gate the 256-channel analyzer. Internal-conversion electrons were measured photographically in 180° uniform-field magnetic spectrographs. Continuous beta-ray spectra were studied with a 180° magnetic spectrometer with a variable uniform field. This spectrometer uses an anthracene

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] B. H. Ketelle, Phys. Rev. **76**, 1256 (1949).
[2] F. D. S. Butement, Proc. Phys. Soc. (London) **A63**, 532 (1950).

crystal detector and has an automatic field-control system.[3]

Chemical Separation and Source Preparation

In order to obtain better data for the Dy^{166} activity, it was desirable to separate the Dy^{166} as completely as possible from its daughter, Ho^{166}. This was done by use of standard ion-exchange-column techniques.[4] In the separations made during this investigation, Dowex-50 resin was used in a column 4 mm in diameter. The elutrient was $0.2M$ α-hydroxyisobutyric acid; its pH was adjusted to approximately 4.0 with ammonium hydroxide. The length of the resin column, which depended upon the exact pH used, was varied between 3 and 6 cm. The column was maintained at approximately 76°C (the boiling point of methyl chloroform). With the column operating under these conditions, the peak of the holmium activity was eluted after approximately 35 min and the dysprosium activity after about 60 min.

The source material used throughout this investigation was dysprosium oxide enriched to 90% in Dy^{164} (supplied by the Stable Isotopes Division, Oak Ridge National Laboratory). The irradiations were made in the Argonne CP-5 reactor in a flux of 3×10^{13} and at the Materials Testing Reactor, Arco, Idaho in a flux of 2×10^{14} neutrons cm^{-2} sec^{-1}. In order to make a separate study of the daughter activity, Ho^{166}, samples of holmium oxide were also irradiated.

For the studies of the continuous beta-ray spectra, the source backing consisted of polyester film with aluminum vacuum coated on both sides (total density about 1 mg/cm^2).[5] The first of two dysprosium sources (in equilibrium[6] with the holmium daughter) and the holmium source were made by preparing a slurry of the active powder in alcohol and depositing it on the backing. A second dysprosium source was made from dysprosium that had been separated in an ion-exchange column. The active material was removed from the elutrient by solvent extraction into a solution of TTA in benzene.[7] This solution was then placed on the backing and dried a drop at a time in an oven at approximately 120°C.

For studies of internal-conversion electrons, holmium sources and some dysprosium sources were made by placing the powdered source material on the adhesive side of commercial cellulose tape; this backing has a density of about 8 mg/cm^2. Other dysprosium sources were made from chemically separated material; these were prepared by drying a portion of the active fraction of the elutrient on an aluminum backing (5 mg/cm^2).

[3] S. B. Burson, D. W. Martin, and L. C. Schmid, Rev. Sci. Instr. **30**, 513 (1959).

[4] B. H. Ketelle and G. E. Boyd, J. Am. Chem. Soc. **69**, 2800 (1947); G. R. Choppin and R. J. Silva, J. Inorg. & Nuclear Chem. **3**, 153 (1956).

[5] Obtained from Alexander Vacuum Research, Inc., 285 Madison Avenue, New York, New York.

[6] "Equilibrium" is here used in reference to a source which has aged for a sufficiently long time so that the Ho daughter no longer exhibits its own characteristic 27-hr period, but rather decays with the 80-hr period of the Dy^{166} parent.

[7] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **114**, 1082 (1959).

EXPERIMENTAL RESULTS

Studies of Internal-Conversion Electrons

The internal-conversion-electron lines observed are listed in Table I along with our interpretations and some relative intensities. Although the decay of the lines was not measured quantitatively, all the lines appeared to decay with the same half-life (within about 30%).

The intensities were calculated from the areas under the line profiles on densitometer traces of the photographic plates. The errors in the relative intensities arise from two sources; first, the error in the correction for the sensitivity of the photographic emulsion; and second, the decomposition of the superimposed line profiles. We estimate that the combined error resulting from these uncertainties is approximately 30%. The energies of the lines are accurate to about 0.3 kev. In particular, as a criterion of accuracy, we refer to the work of Chupp *et al.*[8] who reported a gamma-ray energy of 80.57 kev for the transition in erbium which we measure to be 80.6 kev.

All of the observed lines are assigned to three of the transitions in Ho^{166} (the ones at 82.5, 54.2, and 28.1 kev) and to the 80.6-kev transition in Er^{166}. For the 82.5-kev transition, the K, L_I, and N lines are observed. Its M line is merged with the N line of the 80.6-kev transition. The K/L ratio of the 82.5-kev transition is found to be 7 ± 3.

TABLE I. Data relating to gamma-ray transitions.

Transition energy (kev)	Internal-conversion lines: Energy (kev)	Interpretation	Gamma energy (kev)	Relative intensities: Conversion[b] electrons	Photons[b]	Transition
			Lines in holmium			
28.1 ± 0.3	18.7	L_I	28.1	~12	...	~12
54.2 ± 0.2	45.3	L_{II}	54.2	6 }		
	46.2	L_{III}	54.2	6 } 16	...	16
	52.3	$M_{II,III}$	54.1	4 }		
	53.8	N	54.2	0.4 }		
82.5 ± 0.2	26.6	K	82.2	55 }		
	73.3	L_I	82.6	8 } 63	14[c]	77
	(80.5)[a]	M	(82.4)	≤2 }		
	82.1	N	82.5	~0.2 }		
288 ± 4	...			...	$0.1^{+0.05}_{-0.08}$	0.1
344 ± 2	...			...	$0.3^{+0.1}_{-0.2}$	0.3
375 ± 2	...			...	1.1 ± 0.1	1.1
428 ± 2	...			...	1.4 ± 0.1	1.4
			Lines in erbium			
80.6	22.8	K	80.3	22		
	71.4	L_{II}	80.7	25		
	72.3	L_{III}	80.7	23		
	78.9	M	80.7	~9		
	(80.5)[a]	N	(80.8)	≤2		

[a] These two lines are not resolved.
[b] The data on photon and conversion-line intensities are normalized by use of the experimental value $\alpha_K{}^{82}=4.0$.
[c] All other photon intensities are measured relative to this value.

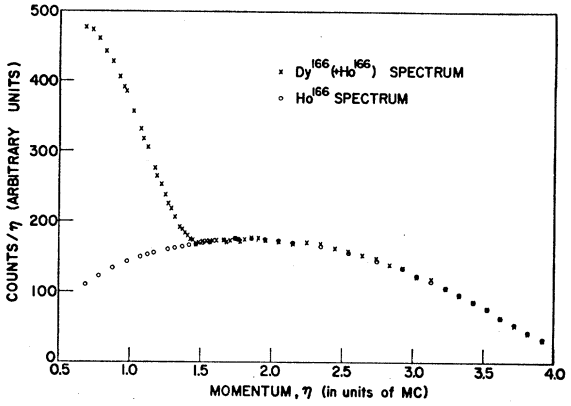

FIG. 1. Beta-ray spectra of Dy^{166} (in equilibrium with the holmium daughter) and Ho^{166}. The statistical uncertainties are less than the dimensions of the experimental points.

The L_{II}, L_{III}, M, and N lines are observed for the 54.2-kev transition. The multipolarity of this transition is deduced from the relative intensities of the L conversion lines (see Table II). The two L lines are observed to be of equal intensity. Of the four possible multipoles ($E1$, $E2$, $M1$, $M2$), $E2$ is the only one for which the L_I line is not predominant. The observed intensity ratios can, therefore, be produced only by a transition which has either pure or primarily $E2$ character. However, the conversion coefficients are such that a substantial admixture of $M1$ could be present without being observed. As will be seen in the discussion of the decay scheme, the 0^- assignment for the ground state of Ho^{166} requires that the 54.2-kev transition be pure.

We have interpreted the 18.7-kev internal-conversion line as an L_I for a 28.1-kev transition. This conclusion is supported by several facts. If this were the K conversion line of a 74.3-kev transition, accompanying L lines would have been visible, but none were observed. Considering the line to be the L_I line of a 28.1-kev transition leads to an excellent energy fit to the 82.5-kev transition when combined with the 54.2-kev transition

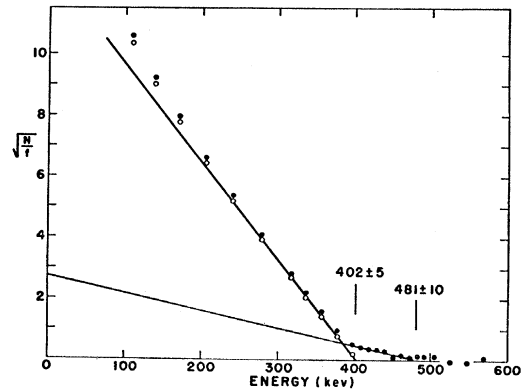

FIG. 2. Fermi plot of the beta-ray spectrum of Dy^{166}. The statistical uncertainties are less than the diameter of the circles indicating the experimental points.

TABLE II. Relative intensities of conversion lines of the 28- and 54-kev transitions compared with the theoretical values for various multipole orders.

Transition energy (kev)	Experimental	Ratio $L_I:L_{II}:L_{III}$ Theoretical[a] $E1$	$E2$	$M1$	$M2$	Character
28.1	1:0:0	1:0.7:1.1	1:110:140	1:0.09:0.02	1:0.07:0.55	$M1$
54.2	0:1:1	1.9:0.7:1	0.03:0.9:1	67:5.7:1	2.9:0.3:1	$E2$

[a] See reference 9.

(28.1+54.2=82.3). The failure to observe the M and N lines is probably due to the fact that they are masked by the K line for the 82.5-kev transition. Since only the L_I line is observed, the transition must have predominantly $M1$ character. An L_{III} line with an intensity no greater than one-fourth of that of the L_I line would have been observable. From this fact it is possible to place an upper limit of 1% for the possible $E2$ content of this transition.

Beta-Ray Spectrum

The beta-ray spectrum of the first dysprosium source (Dy^{166} in equilibrium with the holmium daughter, Ho^{166}) is shown in Fig. 1. Normalized to this, is the spectrum of a pure 27-hr Ho^{166} source. These spectra indicate the relative intensities of the two activities in a dysprosium source in equilibrium with holmium. In order to obtain a more accurate Dy^{166} spectrum, another dysprosium spectrum was recorded for a source that had been separated in an ion-exchange column. In the latter source, the relative intensity of the holmium was about 1/7 of that in the original dysprosium source.

The Fermi plot of the Dy^{166} spectrum from the separated sample, after subtraction of the Ho^{166} spectrum, is shown in Fig. 2. For the higher energy component, the straight line represents a least-squares fit to the seven points between 475 and 405 kev. Because of the small number of points for this component, no conclusion about its shape could be reached; therefore, it was assumed to be linear. For the lower energy component, the straight line represents a least-squares fit to the seven points between 400 and 240 kev. The deviation from linearity below 240 kev is probably due to scattering in the source and from the backing.

The decay scheme which is proposed later in this report requires two additional beta-ray branches; these

TABLE III. Summary of beta-ray components.

Energy (kev)	Relative intensity (percent)	Log ft
481±10	5	7.4
402±5	92	6.0
114[a]	≤0.1	≥7.1
56[a]	2.8	4.8

[a] The data for these two components are calculated from the gamma-ray energies and intensities and the level scheme shown in Fig. 6.

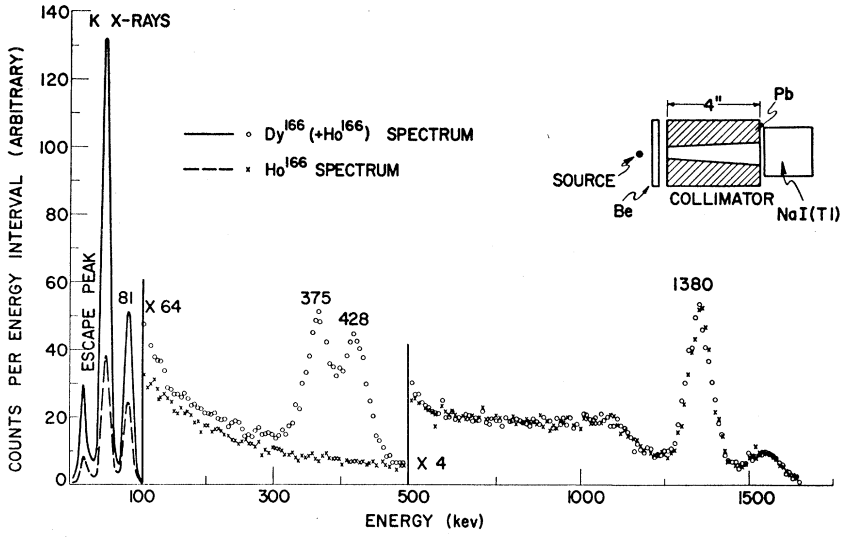

FIG. 3. Gamma-ray spectra of Dy^{166} (in equilibrium with the holmium daughter) and Ho^{166}. The statistical uncertainties are less than the dimensions of the experimental points.

components are both below 120 kev and therefore would not be observed in this spectrum. For completeness these two components are included in Table III which summarizes these data.

A measurement of the half-life of Dy^{166} was made with the original dysprosium beta-ray source. A set of four points ($\eta=0.98$, 1.47, 2.55, and 2.74 on Fig. 1) was followed for a period of one month. In order to minimize the effect of any drifts in the apparatus, each of these four points was selected where the counting rate is a slowly varying function of the momentum. Initially these data showed a small amount of 27-hr activity that resulted from the production of an excess of Ho^{166} by neutron capture in Ho^{165}. [See Eq. (1).] No indication of impurities of longer half-life was observed at the end of one month. An average of the four determinations gives a value of 80.2 ± 0.5 hr for the half-life of Dy^{166}.

Scintillation Studies

The scintillation spectrum for a dysprosium source (in equilibrium with the holmium daughter) is shown in Fig. 3. Normalized to this in the region above 500 kev is the spectrum of a pure holmium source. In Fig. 4 is shown a Dy^{166} spectrum with the holmium subtracted. This spectrum was obtained from a source in which the relative holmium activity had been reduced by a factor of six by means of a separation in an ion-exchange column. The dashed lines in the figure show the energies and relative intensities of the individual components that are presumed to be present. Of the energies reported (Table I, column 1) for the four higher energy transitions, the values for the 428- and 375-kev radiations were obtained from this decomposition of the "singles" spectrum. The energies for the 344- and 288-kev gamma rays were taken from the coincidence

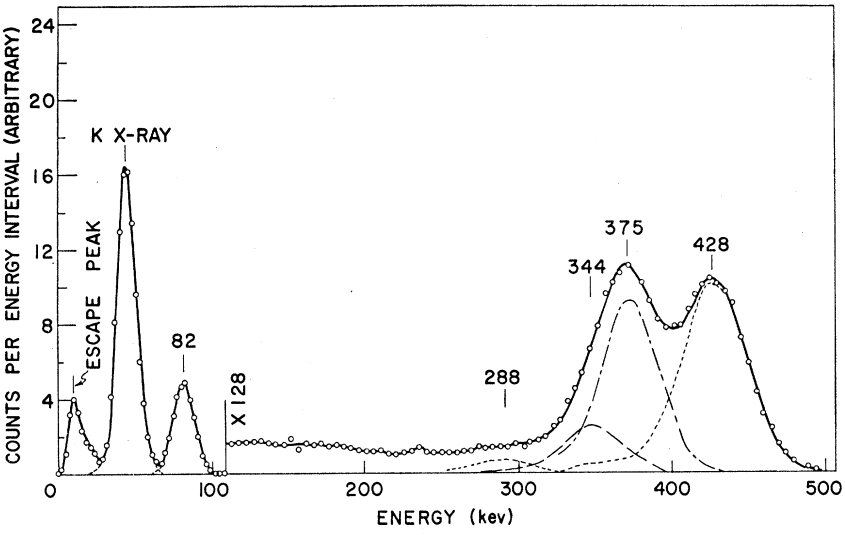

FIG. 4. Gamma-ray spectrum of Dy^{166}. The dashed lines show the individual photopeaks presumed to be present. The solid curve represents the sum of the components shown. All statistical uncertainties are less than the diameter of the circles indicating the experimental points. The experimental arrangement is the same as in Fig. 3.

TABLE IV. Values of α_K and K/L for the 82- and 80-kev transitions compared with theoretical predictions for various multipole orders.

Transition energy (kev)	α_K Experimental	α_K Theoretical $E1$	$E2$	$E3$	$M1$	$M2$	K/L Experimental	K/L Theoretical $E1$	$E2$	$E3$	$M1$	$M2$	Character
82.5	4.0±0.6	0.44	1.6	4.2	4.0	38	7±3	6.3	0.5	0.04	7.4	3.2	$M1$
80.6	1.7±0.3	0.46	1.6	3.7	4.6	44	0.45±0.15	6.0	0.4	0.03	7.3	3.1	$E2$

data discussed below. The spectral shapes of single gamma rays were approximated by those of Au^{198} (412 kev), Cr^{51} (323 kev), and Ho^{166} (80-kev gamma ray and 48-kev K x-rays). The solid curve, which is to be compared with the experimental points, represents the sum of the individual components as they are shown. A summary of the relative photon intensities calculated from this scintillation spectrum is presented in column 6 of Table I.

As can be seen in Fig. 4, the scintillation spectrum for Dy^{166} does not show any evidence of the 54-kev transition whose conversion lines were observed (see Table I). Hence, since the transition energy of 54 kev is too low to produce K conversion in holmium, the K x-ray peak must be due almost entirely to K conversion of the 82-kev transition. (The K x rays following internal conversion of the four higher energy transitions should be completely negligible in view of the low intensity of these gamma rays.) Thus the K conversion coefficient for the 82-kev transition, α_K^{82}, can be calculated from the spectrum in Fig. 4. After correcting for detector efficiency and fluorescence yield, a value of $\alpha_K^{82}=4.0\pm0.6$ results from these data. Table IV presents a comparison of this value with the theoretical values[9] of α_K for transitions of various multipolarities; the K/L ratio calculated from the data in Table I is also included in Table IV along with the corresponding theoretical values. These data indicate that the 82-kev transition has primarily $M1$ character.

In order to check the accuracy of the calculation of α_K^{82} made above, the data in Fig. 3 were used to carry out a similar computation for the 80.6-kev transition in erbium. This transition is from the first excited state to the ground state of an even-even nucleus and is thus presumed to have pure $E2$ character. The $E2$ character has been verified by gamma-gamma angular correlation experiments.[10] The calculation for this transition gives a value $\alpha_K^{80}=1.7\pm0.3$; the comparable theoretical value is $\alpha_K^{80}(\text{theor.})=1.60$. This agreement indicates that there is probably no large error in these calculations. The value of α_K and the K/L ratio for this transition are included in Table IV.

The results of the most interesting gamma-gamma coincidence measurements are shown in Fig. 5. These spectra were obtained with a separated dysprosium sample; the holmium content at the time of these runs was only one-fourth of the equilibrium amount. Figure 5(a) shows a coincidence run with the single-channel analyzer set to accept pulses from the 82-kev photopeak. Figure 5(b) represents a coincidence spectrum taken when the single-channel analyzer was moved to the low-energy side of the x-ray peak. This side of the x-ray peak was selected in order to minimize any coincidences due to the 54-kev radiation. In contrast, Fig. 5(c) shows the spectrum obtained when the single channel was moved to the high-energy side of the x ray in order to enhance any effects due to the 54-kev transition. It was found that the number of coincidences in the 288- and 344-kev photopeaks per single-channel count was nearly the same for these three experiments. On the other hand, the 375-kev peak, not present in (a) and barely observable in (b), is approximately as intense as the other two when the single channel is set at the energy at which the 54-kev radiation is expected to be found. From these experiments, it can be concluded that the 375-kev gamma ray is in coincidence with the 54-kev radiation (unobserved in the "singles" spectrum), but not with the 82-kev

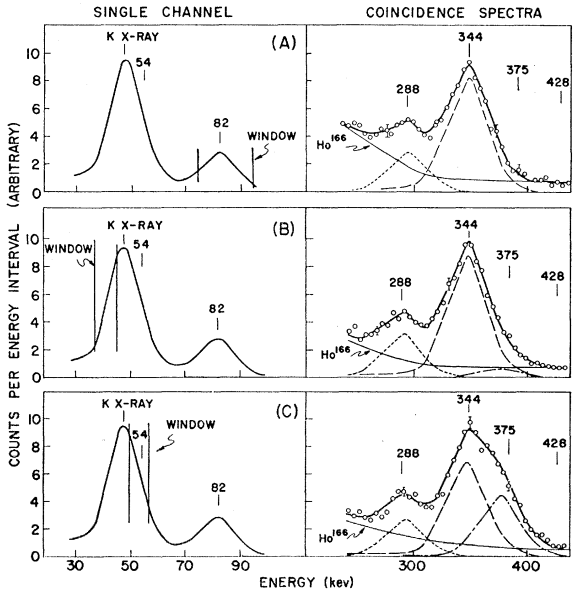

FIG. 5. Gamma-gamma coincidence spectra. The dashed lines show the decompositions of these spectra into the constituent photopeaks.

[8] E. L. Chupp, J. W. M. DuMond, F. J. Gordon, R. C. Jopson, and H. Mark, Phys. Rev. **112**, 518 (1958).

[9] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958).

[10] J. S. Fraser and J. C. D. Milton, Phys. Rev. **98**, 1173(A) (1955).

gamma ray. The 288- and 344-kev gamma rays are in coincidence with the 82-kev radiation and the K x rays which (as mentioned earlier) arise primarily from internal conversion of the 82-kev transition.

In addition to the experiments described above, a thorough survey of the entire spectrum was made with the single-channel analyzer in a search for other coincident relationships, but none were found. (In all cases it was necessary in the analysis to take into consideration the effects of the daughter activity.)

From beta-gamma coincidence measurements, it was possible to determine the total decay energy. Standard aluminum absorption methods were used to measure the end-point energies of the beta-ray components in coincidence with each particular gamma ray. It was found that the 82-kev gamma ray is in coincidence with a beta-ray branch whose maximum energy is 400 ± 20 kev (half-thickness$=10$ mg/cm^2); this is assumed to be the 402 ± 5-kev component found with the magnetic spectrometer. None of the higher energy gamma rays were found to be in coincidence with this beta-ray branch.

With no absorber between the source and anthracene crystal, except about $\frac{1}{8}$ in. of air, there were some beta-gamma coincidences with the 375- and 428-kev gamma rays. No definite conclusions could be inferred from the coincidences with the 375-kev photopeak, since these events could as well be attributed to internal-conversion electrons as to beta rays. However, the coincidences with the 428-kev gamma ray can be ascribed to beta rays, since as has been seen, this radiation is in coincidence with no other gamma transitions from which conversion electrons might originate. Although the coincidence rate was low, the attenuation in aluminum (half-value thickness$=0.6\pm0.3$ mg/cm^2) corresponds approximately to an endpoint energy of 55 kev.

VERIFICATION OF ASSIGNMENT OF THE 80-HR ACTIVITY

Those aspects of the experimental results which substantiate the isotopic assignment originally made by Ketelle and Butement are summarized here. Table I lists the internal-conversion electron lines observed in the Dy^{166} sources. Over a period of 15 days, these lines all appeared to decay at the same rate (half-life$\approx$80 hr). One set of these lines is interpreted as representing the 80.6-kev transition in erbium, following the decay of Ho^{166}. This interpretation is corroborated by the fact that a pure Ho^{166} source (made by neutron capture in stable holmium) exhibited a set of lines with identical energies and relative intensities. Furthermore, this set of lines was reduced (by a factor of 4 to 5) in intensity relative to the other lines on plates obtained with a source of Dy^{166} from which holmium had been removed by means of the ion-exchange column. Thus, the 27-hr holmium could only be produced as the decay product of some other activity, which could only be Dy^{166}.

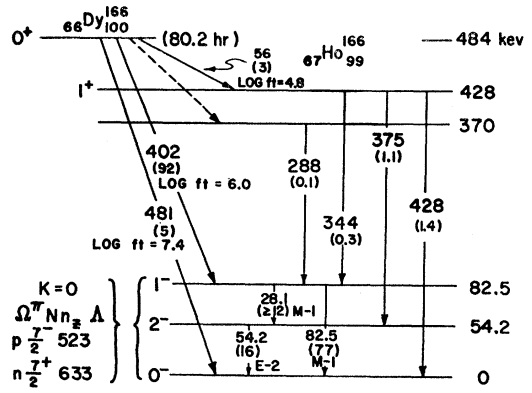

FIG. 6. Proposed decay scheme for $_{66}Dy^{166}$. The relative transition intensities (percent of decays) are shown in parentheses.

The same arguments hold for the data on the beta-ray spectrum. Figure 1 shows that the portion of the dysprosium spectrum above 500 kev is identical with that of the pure Ho^{166} source. In the dysprosium source the entire spectrum decays with an 80-hr half-life in contrast to the characteristic 27-hr half-life of Ho^{166}. Also, when the dysprosium is chemically separated from the holmium, one observes that the portion of the dysprosium spectrum above 500 kev grows back in at the rate predicted from the half-lives and parent-daughter relationships.

Again from the scintillation data (Fig. 3), the similarity of the two spectra, the apparent half-life of the Ho^{166} radiations, and the growth of the Ho^{166} gamma rays after chemical separation are facts which confirm the isotopic assignment of the 80-hr activity to Dy^{166}.

DECAY SCHEME

The proposed decay scheme is shown in Fig. 6. It is consistent with all of the experimental data. The 428-kev transition was not observed in coincidence with any other gamma ray and the 375-54, 288-82, and 344-82 kev cascades were all observed. The energy fits between the cascades and the cross-over transitions agree within experimental uncertainties.

As noted in Table I, in order to obtain relative transition probabilities, the two sets of relative-intensity data (scintillation and spectrographic) are normalized by using the experimentally determined value of $\alpha_K{}^{82}=4.0$. These transition probabilities (the numbers in parentheses on the decay scheme) have been reduced to percentages of the total number of decays by incorporating the beta-ray branching data from the magnetic spectrometer measurements (Table III).

The log ft values of 7.4 and 6.0 for the 481- and 402-kev beta-ray branches indicate that these transitions are first forbidden. The log ft value of the branch to the 428-kev level is determined[11] by use of a relative

[11] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).

intensity of 3% as calculated from the intensities of the gamma transitions. The latter log ft value of about 4.8 is significant in that it suggests that this branch is allowed.

For any character which might be assigned to the 28-kev transition (except $E1$), the relative transition intensity is very nearly equal to that of the internal-conversion lines. Although there is considerable uncertainty in this transition intensity, the value calculated (considered together with that of the 54-kev transition), is consistent with this cascade.

There are three other gamma-ray transitions which might occur between the levels indicated: 58, 316, and 370 kev. If the 58-kev transition, between the 428- and 370-kev levels, were present and highly converted, it could be sufficiently intense to obviate the beta-ray branch to the 370-kev level and still be unobservable. If a 316-kev transition occurs between the 370- and 54-kev levels, it must have an intensity less than about 25% of that of the 288-kev transition. The possible 370-kev transition to the ground state would be indistinguishable from the 375-kev gamma ray in the "singles" spectrum. However, interpretation of the coincidence experiments indicates that this ground-state transition, if present must be weak compared to the 375-kev gamma ray.

Since $_{66}Dy^{166}$ is an even-even nucleus, its ground-state spin and parity are assumed to be 0^+. On the basis of the analysis of the beta spectrum and beta-gamma angular correlation measurements of Graham *et al.*,[12] the spin and parity of the 27-hr ground state of $_{67}Ho^{166}$ is assumed to be 0^-.[12a] It follows from the latter spin assignment, that the gamma-ray transitions to the Ho^{166} ground state must be pure transitions (i.e., they can not be mixtures of different multipole order). Thus, the predominantly $E2$ character of the 54-kev transition indicates that the first excited state has spin and parity 2^-. Similarly, the $M1$ character of the 82-kev transition indicates that the 82-kev level is a 1^- state. The only possible assignments which are consistent with the character of the beta decay to the 428-kev state (log $ft \approx 4.8$) are 0^+ and 1^+. The fact that this level does decay to the ground state by gamma-ray emission eliminates the 0^+ possibility (since monopole photons do not exist).

[12] R. L. Graham, J. L. Wolfson, and M. A. Clark, Phys. Rev. **98**, 1173(A) (1955); see also J. M. Cork, M. K. Brice, R. G. Helmer, and R. M. Woods, Jr., Phys. Rev. **110**, 526 (1958).

[12a] *Note added in proof.*—During the preparation of this report, atomic beam experiments were carried out at our request by Dr. L. S. Goodman and Dr. W. J. Childs of the Argonne National Laboratory in order to establish more firmly the ground-state spin of Ho^{166}. A similar study has been conducted at the University of California, Berkeley. Both investigations concur in supporting the zero spin assignment to this state. The results were presented in a joint paper [L. S. Goodman, W. J. Childs, Richard Marrus, Ingvar P. K. Lindgren, and Amado Y. Cabezas, Bull. Am. Phys. Soc. **5**, 344 (1960)].

INTERPRETATION OF ENERGY LEVELS IN Ho^{166}

Holmium-166 lies in the region $155<A<185$ in which nuclear deformations might be expected. In this region there are numerous cases in which experimentally observed properties conform to the predictions of the "unified" model of Bohr, Mottelson, Nilsson, and others. Most of the experimental and theoretical work has been concerned with even-even and odd-A nuclei. Except for some treatments relating to ground-state spins, there is a dearth of both theoretical work and experimental data on odd-odd nuclei.

As previously noted, the properties assigned to the excited states are predicated on the assumption that the ground state of Ho^{166} has spin and parity 0^-. Although this assumption is based on good experimental evidence, this spin has not been directly measured. It is possible to present an interpretation of the first two excited states which is consistent with this assumption.

The spin 0^- for the holmium ground state is consistent with the spins measured for neighboring odd-A nuclei, Ho^{165} with 67 protons and Er^{167} with 99 neutrons. The spin of $_{67}Ho^{165}$ has been measured as $\frac{7}{2}$[13]; Mottelson and Nilsson have interpreted this as the Nilsson level $\frac{7}{2}^-[523]$.[14] (The notation used here for the asymptotic quantum numbers is the same as in reference 14, namely, $\Omega\pi[Nn_z\Lambda]$.) The spin of Er^{167}, which has 99 neutrons, has been measured as $\frac{7}{2}$[15]; this has been interpreted as the $\frac{7}{2}^+[633]$ level.[14] Apparently, in Ho^{166} these two odd particles couple to produce a state of zero spin and odd parity. A long-lived ($\gtrsim 30$ yr) isomer of Ho^{166} also exists. The high spin necessary for this metastability presumably results from a different coupling of these same two particles to produce a state of spin 7. The existence of this pair of states is in agreement with the theory that predicts the spin of the ground state of an odd-odd nucleus to be one of the two states given by $I=K=\Omega=|\Omega_p \pm \Omega_n|$, where p and n refer to the odd proton and neutron, respectively. It is reasonable to assume that the 99th and 100th neutrons in the parent nucleus Dy^{166} are in the same level as the 99th neutron in Dy^{165}, that is, the $\frac{7}{2}^+[633]$ level. Then the beta decay to the ground state should be characterized by the following changes in quantum numbers: $\Delta I=0$, $\Delta K=0$, $\Delta N=-1$, $\Delta n_z=-1$, $\Delta\Lambda=0$. According to the asymptotic selection rules tabulated in reference 14, this beta transition would be unhindered ordinary first forbidden. This is consistent with the observed log ft value of 7.4.

The 54-kev level, which has spin 2, is presumed to be an excited state of a rotational band (with $K=0$) based on the ground state. The second excited state,

[13] J. E. Mack, Revs. Modern Phys. **22**, 64 (1950); J. M. Baker and B. Bleaney, Proc. Phys. Soc. (London) **A68**, 1090 (1955).

[14] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **1**, No. 8 (1959).

[15] B. Bleaney and H. E. D. Scovil, Proc. Phys. Soc. (London) **A68**, 204 (1951).

which has spin 1, might have either of two values for the projection of its spin on the symmetry axis, that is, $K=0$ or 1. The two radiations which de-excite this level are both essentially pure $M1$ transitions. By comparing the experimental ratio of the reduced transition probabilities to the theoretical values, we can distinguish between the two possible values of K. (The gamma-ray intensity for the 28-kev transition was computed by use of $\alpha_{LI}^{28}=9.6$ from reference 9.) The results of such a comparison are

	Theoretical $K=1$	Theoretical $K=0$	Experimental
$\frac{B(1;1\to 0)}{B(1;1\to 2)}=\left(\frac{\langle 11K-K\vert 1100\rangle}{\langle 11K-K\vert 1120\rangle}\right)^2$	2.0	0.5	0.4±0.2

Thus it is clear that the second excited state also has $K=0$ and is probably another member of the rotational band based on the ground state. The fact that the 82-kev state has $K=0$ explains why no $E2$ admixture was observed in the 28-kev transition. The $E2$ transition probability between these two levels should be proportional to the Clebsch-Gordon coefficient

$$\langle I_i L K_i K_f - K_i \vert I_i L I_f K_f\rangle = \langle 1200\vert 1220\rangle.$$

This coefficient is zero, so the $E2$ transition probability vanishes.

If our interpretation of the experimental data is correct and the first two excited states are in fact members of a $K=0$ band based on the ground state, then two features of this relationship should be noted. First, both odd and even spin states are present. Second, the expression which governs the energy spacing of the states must be such as to permit the inversion of the first and second excited states. In recent conversations with Dr. John O. Rasmussen, University of California, Berkeley, California, he suggested that one might expect to find such a level sequence in an odd-odd nucleus.

TABLE V. Comparison of experimental transition intensities from the 428-kev level with theoretical transition probabilities.

	Theoretical $K=1$	Theoretical $K=0$	Experimental
$\frac{\omega^3B(1;1\to 0)}{\omega^3B(1;1\to 2)}$	3.0	0.75	
$=$	1.0	1.0	
$\frac{\omega^3B(1;1\to 1)}{\omega^5B(2;1\to 0)}$	2.3	0	$\frac{T(1\to 0)}{T(1\to 2)}=\frac{1.3}{1.0}$
$\frac{\omega^5B(2;1\to 2)}{\omega^5B(2;1\to 1)}$	0	0	$\frac{T(1\to 2)}{T(1\to 1)}=\frac{1.0}{0.25}$
$=$	2.5	0	
	1.0	1.0	

The information available concerning the excited state at 370 kev is too meager to attempt any interpretation.

From the character of the beta decay to the 428-kev level, this state has been assigned the spin and parity 1^+. For this spin there is again a choice between the two values $K=0$ and $K=1$. Although the ground-state transition must be pure dipole radiation, the other transitions might be mixtures of dipole and quadrupole radiation. In Table V, the experimental gamma-ray transition intensities are compared with the theoretical transition probabilities. From this comparison, it is clear that the choice $K=1$ is incompatible with the experimental data. For the alternative value $K=0$, the agreement, while not striking, seems not inconsistent with the experimental uncertainties and the limitations of the theory which has been invoked.

Note added in proof.—After this paper was submitted for publication, the results of an independent investigation on Dy^{166} [J. S. Geiger, R. L. Graham, and G. T. Ewan, Bull. Am. Phys. Soc. **5**, 255 (1960)] appeared. These data are in substantial accord with the experimental and theoretical conclusions contained in our preliminary paper [R. G. Helmer and S. B. Burson, Bull. Am. Phys. Soc. **4**, 427 (1959)] as well as presented in this report.