Decay of $_{65}Tb^{160}$ (71 Day)

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By means of 180° internal-conversion electron spectrometers and the scintillation coincidence spectrometer, the radiations of $_{65}Tb^{160}$ (71 day) have been studied. In addition to many of the previously reported transitions in Dy^{160}, three new gamma rays of 0.759, 1.17, and 1.26 Mev are observed. By using the energy values determined from the internal conversion studies together with beta-gamma and gamma-gamma coincidence results a decay scheme is deduced which is consistent with the experiments discussed.

INTRODUCTION

Neutron capture in terbium produces a long-lived activity first observed by Bothe[1] who assigned to it a half-life of 73.5 days. The value determined at this laboratory[2] was 71±1 days. In addition to gamma rays Bothe's absorption measurements indicated the presence of several beta rays, the one of highest energy being about 0.75 Mev. From the fact that Tb exists in nature only as stable Tb^{159}, it was deduced that the activity belonged to Tb^{160}. This assignment was confirmed by mass spectrometer measurements.[3] The beta spectrum was resolved by Cork *et al.*[4] into two components of 546 and 882 kev and the presence of numerous gamma rays was ascertained by internal conversion electron measurements. Burson *et al.*[2] resolved the beta spectrum into three components with end-point energies of 860, 521, and 396 kev. Internal conversion lines corresponding to five gamma rays were also observed. Salmi's measurement[5] of the beta spectrum with a double-focusing spectrometer indicated only two components with end-point energies of 886 and 546 kev. Shavtvalov[6] reports a 40 percent beta-ray branch of 850 kev and a 60 percent component referred to as "540, 590 kev." His measurements also indicate that internal conversion electrons representing the 86.3-kev transition are in coincidence predominantly with the lower-energy beta group. McGowan[7] reports that the gamma ray of about 85 kev is to be associated with decay from a metastable state whose half-life is 1.8×10^{-9} second. The delayed coincidence measurements indicate that this state follows the highest-energy beta ray. His measurement of the K-shell conversion coefficient is in agreement with the theoretical value for an $E2$ transition.

The present study was commenced in an effort to resolve the discrepancies between the various measurements of the beta spectrum and to arrive at a tenable decay scheme. The earliest measurements with our scintillation coincidence spectrometer revealed the presence of gamma rays of higher energy than any heretofore reported. Since these transitions could not be fitted into the previously proposed energy levels of Dy^{160}, coincidence measurements were undertaken in an effort to arrive at a more consistent decay scheme.

INTERNAL CONVERSION MEASUREMENTS

The internal conversion electron studies were carried out using the 180° photographic spectrometers previously described.[8]

The most comprehensive measurements on the internal conversion electron groups are those reported by Cork *et al.*[4] They report 26 conversion lines and 13 photo lines (using a lead radiator) and from these deduce the presence of 12 gamma rays. Our study of the internal conversion spectrum indicates the presence of three additional gamma rays. Our plates, however, do not show lines representing several of the gamma rays reported in the Michigan study. Evidently, the magnetic fields of the spectrometers were adjusted so that different portions of the spectrum were included in the region of maximum sensitivity. Our exposures in the neighborhood of 400 kev were relatively weak, and could have been examined more extensively by longer exposures and stronger sources. Probably the same considerations explain why the high-energy gamma rays were overlooked by the other investigators.

The results of our study of the internal conversion spectrum are tabulated in Tables I and II. To provide a complete presentation of the available information, the gamma rays found by Cork *et al.* are also listed in Table II.

SCINTILLATION EXPERIMENTS

The scintillation studies were made using the scintillation coincidence spectrometer.[9] This instrument consists of two scintillation spectrometers, one equipped with a ten-channel pulse-height analyzer, and the other with a single-channel analyzer. Either may be operated independently, or the single channel may be operated

[1] W. Bothe, Naturwiss. **31**, 551 (1943); Z. Naturforsch. **1**, 179 (1946).
[2] Burson, Blair, and Saxon, Phys. Rev. **77**, 403 (1950).
[3] Inghram, Hayden, and Hess, Phys. Rev. **71**, 643 (1947).
[4] Cork, Shreffler, and Fowler, Phys. Rev. **74**, 240 (1948); Cork, Branyan, Rutledge, Stoddard, and LeBlanc, Phys. Rev. **78**, 304 (1950).
[5] E. Salmi, thesis, University of Michigan, 1950 (unpublished).
[6] L. J. Shavtvalov, Izvestia Akad. Nauk SSSR Ser. Fiz. **17**, No. 4, 503 (1953).
[7] F. K. McGowan, Phys. Rev. **85**, 142, 151 (1952).
[8] Rutledge, Cork, and Burson, Phys. Rev. **86**, 775 (1952).
[9] S. B. Burson and W. C. Jordan, Phys. Rev. **91**, 498 (1953).

TABLE I. Internal conversion electrons associated with $_{65}Tb^{160}$ (71 day).

Electron energy (kev)	Relative intensity	Interpretation	Transition energy (kev)
32.6	9	K	86.4
36.8		Auger (K-L-L)	
39.6		K	93.4
42.2		Auger (K-L-M)	
43.6		Auger (K-L-M)	
77.6	10[a]	L_2	86.2
78.5		L_3	86.3
84.4	2	$M_{2,3}$	86.2
85.8		$N_{2,3}$	86.1
142.3		K	196.1
160.5		K	214.3
187.5		L	196.1
193.8		M	195.6
195.5		N	195.8
206.7		L	215.3
243.8		K	297.6
288.9		L	297.5
337.5		K	391.3
705		K	759
819		K	873
865		L	874
906		K	960
952		L	960
1120		K	1174
1211		K	1265

[a] $L_1 \ll L_2 \approx L_3$.

to gate a coincidence circuit (resolving time ~ 2 microseconds) built into the ten-channel analyzer. The RCA 5819 probe assemblies and detecting crystals were provided by Swank and Moenich of this laboratory, and patterned after their designs.[10] For gamma-ray detection, NaI(Tl) crystals (0.375 in. thick$\times$1.25 in. in diameter) were used. For beta-ray detection, an anthracene crystal (0.5 in. thick$\times$1.5 in. in diameter) provided with a thin aluminum window (2.8 mg/cm^2) was used. The ten-channel analyzer is provided with a window amplifier. By adjusting the photomultiplier voltage, and the gains of the linear amplifier and the window amplifier, any portion of the spectrum can be examined in as much detail as desired. (This apparatus is to be described in greater detail in a separate publication.)

The Normal Photon Spectrum

Using the NaI(Tl) crystal, together with an aluminum absorber sufficiently thick to remove all charged radiation, the pulse-height distribution was determined with the ten-channel analyzer. (Such a single crystal analysis shall hereinafter be referred to as a "normal distribution" as opposed to a "coincidence distribution.")

The normal spectrum for Tb is shown in Fig. 1. To obtain this curve, the single-channel probe of the coincidence circuit was removed from the proximity of the source to reduce scattering effects. The source was placed about ten inches from the detecting crystal to eliminate "sum-lines" (spurious peaks appearing in the spectrum caused by simultaneous detection of two different gamma rays). The resolution of the spectrometer (full-width at half-maximum) was measured to be 13 percent for the 662-kev gamma ray of Cs^{137} and varied from 22 percent at 86.3 kev to approximately 10 percent at about 1.0 Mev. The window width and gain of the analyzer were adjusted so that in the highest energy region the windows were about 28 kev wide. The 1.17, 1.26-Mev peak is thus defined by about ten experimental points. Each time the differential analyzer was readjusted, from three to five channels were allowed to overlap the previous setting to insure accurate fitting together of the adjacent regions of the spectrum. In the lower-energy regions of the spectrum narrower channels were used, being about 5 kev wide for the region containing the 86.3-kev gamma ray and below. In all cases, the counting was continued to obtain statistical accuracy of about 1 percent at each point.

Ten peaks are clearly resolved. The peak with the highest energy represents two gamma rays to be identified with the 1.17- and 1.26-Mev transitions observed in the internal conversion studies. It is evident from its position relative to the Co^{60} calibration lines that the 1.17-Mev radiation predominates, the 1.26-Mev photopeak appearing only as a slight broadening of the high-energy side. The peak at about 900 kev is seen to be broad and clearly due to two radiations close together in energy. These are identified as the two gamma rays of 873 and 960 kev. From the low amplitude of the 1.17 and 1.26-Mev photopeak, it may be safely concluded that the Compton distribution associated with it makes a relatively small contribution to the background underlying the 900-kev peak. The broad peak centered at about 650 kev can be primarily attributed to the Compton distribution due to the 873 and 960-kev gamma rays. It is impossible to ascertain from the shape of this distribution to what extent the 759-kev gamma ray (detected by internal conversion) contributes. A small peak appears at about 400 kev. This peak is interpreted as representing either the 391

TABLE II. Gamma transitions in Dy^{160}.

Cork *et al.* Energy (kev)	Present Energy (kev)	K/L
86.5	86.3±0.3	0.9±0.3
92.6	93.4±0.5	
176.2		
196.4	196.1±0.6	~3
214.7	214.8±0.6	>2
282.0		
297.8	297.6±0.8	>5
375.2		
391.0	391.3±2.0	
410.3		
	759 ±3	
876	873 ±4	~5
962	960 ±4	~5
	1174 ±8	
	1265 ±8	

[10] R. K. Swank and J. S. Moenich, Rev. Sci. Instr. 23, 502, 503 (1952).

or 410-kev gamma rays, or both. Two strong peaks are resolved at about 296 and 206 kev, using the 279-kev gamma ray of Hg^{203} for calibration. The 296-kev peak is associated with the 298-kev transition. While the peak at 206 kev appears to be a single peak, it is somewhat broader than is to be expected from the resolution of the instrument. This, together with the fact that its energy lies between the 196- and 215-kev gamma rays, would indicate that the peak probably represents this pair. The lowest-energy gamma ray which was detected is assigned an energy of 86 kev using the 85-kev peak of Tm^{170} for calibration. This is identified as the 86.3-kev radiation. The two remaining peaks are interpreted as the K x-ray of Dy^{160} and its associated escape peak, produced when the x-rays of iodine escape from the detecting crystal.

Coincidence Experiments

Because of the many transitions associated with the excited states of Dy^{160}, it is difficult to arrive at a unique arrangement of the energy levels. The experimental errors present in energy measurements alone allow various possible decay schemes such as those previously proposed.[2,4] The most feasible method by which the number of such possible combinations can be reduced is by means of coincidence experiments.

All of the coincidence experiments were performed with the probes placed coaxially inside a cylindrical lead shield whose inside diameter was 4 in. The beta-gamma coincidence measurements were made using the anthracene crystal for the beta detector in the probe of the single-channel analyzer. The analyzer was set in the integral position, and the bias adjusted to reject most of the noise pulses of low amplitude. The ten-channel analyzer was set successively on each of the photopeaks and aluminum absorption curves run on the beta rays in coincidence with each peak. During the gamma-gamma measurements, the crystal faces were about 1.5 cm apart and aluminum filters (350 mg/cm²) placed in front of each crystal holder to prevent charged radiation from being detected.

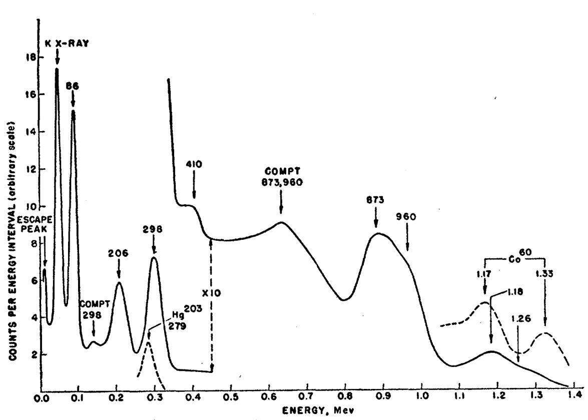

FIG. 1. Gamma-ray spectrum of $_{65}Tb^{160}$ (71 day). NaI(Tl) pulse-height distribution.

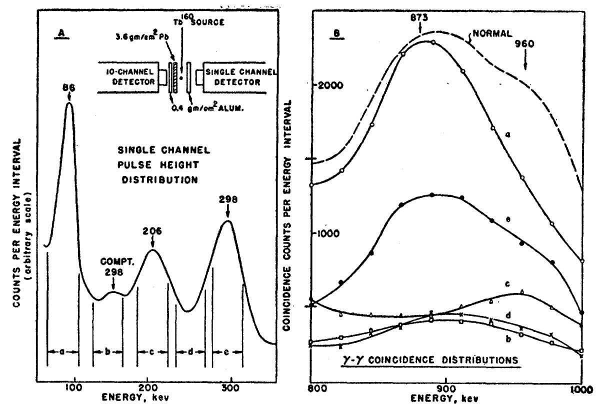

FIG. 2. Coincidence pulse-height distributions for $_{65}Tb^{160}$ (71 day). In B five coincidence distributions are plotted corresponding to the single-channel settings indicated in A. The dashed curve in B represents the normal pulse-height distribution for the region in which the coincidence distributions are recorded.

Figure 2 presents the results of a typical set of gamma-gamma coincidence measurements. Figure 2A shows a normal distribution obtained with the single-channel analyzer using a 5-kev window. After the single-channel normal distribution is so obtained, the ten-channel analyzer is adjusted so that it shows the normal distribution shown by the dashed curve of Fig. 2B. The window of the single-channel analyzer is then opened wide enough to accept most of the pulses contained in a given peak and the corresponding ten-channel coincidence distribution recorded. The curves in "B" represent the coincidence distributions corresponding to the various settings of the single-channel analyzer indicated as "a" through "e" in "A". It is readily apparent from curve "a" that the 86.3-kev gamma ray is predominately in coincidence with the 873-kev radiation. Curve "c" shows that most, if not all, of the coincidences associated with the 206-kev peak are with the 960-kev radiation. Curve "e" is very similar to the normal distribution, from which it may be inferred that the 298-kev gamma ray is in coincidence with both the 873 and 960-kev transitions. Curves "b" and "d" show that the coincidence rates fall off markedly in the valleys between the peaks represented in the single-channel distribution. Figure 2 is representative of a large number of such experiments.

One major advantage of this technique is that rapid comparisons can be made between the normal and coincidence spectra, so that very small peak shifts in the coincidence spectrum can be detected which might otherwise be rejected as being due to drift of the instrument or to statistical uncertainty if the same comparison were to be obtained by a single-channel analyzer.

Interpretation of many of the coincidence experiments is confused by the complex manner in which high-energy gamma rays are detected by the NaI crystals. Since in this study the gamma ray of maximum

TABLE III. Results of coincidence experiments. Transition energies are designated in kev. *A*—Coincidence observed, interpretation unambiguous. *B*—Coincidence observed, interpretation probably correct. *X*—Coincidence required by decay scheme of Fig. 4 but concluded to be below detection limit of apparatus. Numbers refer to paragraphs presenting related experimental details.

		Gamma												
		86.3	93	196	215	298	375	391	410	759	873	960 957[a]	1170	1260
Beta	860	*B*3	*X*	*X*	*X*		*X*		*X*		*A*1	*A*1		
	520	*B*3	*X*	*A*2	*A*2	*A*2	*X*	*X*	*X*	*X*	*B*1	*B*1	*A*2	*X*2
Gamma	1260													
	1170	*A*4												
	960					*B*7								
	957[a]	*X*[a]			*B*10[a]									
	873	*A*5				*A*7								
	759	*X*		*B*11	*B*11				*X*					
	410	*X*	*X*			*X*	*X*	*X*						
	391	*X*		*X*	*X*		*X*							
	375	*X*	*X*	*X*	*X*	*X*								
	298	*A*6		*X*9	*X*9									
	215	*A*6	*X*	*A*8										
	196	*A*6	*X*											
	93	*X*												

[a] The 957-kev transition is grouped with the 960 since they are experimentally indistinguishable.

energy is only slightly in excess of the threshold for pair production, this process presents no serious problem. In coincidence experiments, in which the two detecting crystals are in close juxtaposition, the geometry is excellent for detecting in one crystal a large fraction of the backscattered quanta resulting from Compton scattering in the opposite crystal. For incident gamma rays ranging from 0.7 to 1.3 Mev, the energy of the secondary radiation scattered at 180 degrees increases from 180 kev to only about 210 kev, and approaches approximately 250 kev as the energy of the primary radiation increases without limit. For any given primary gamma ray, the energy of the secondary photons increases slowly as the scattering angle is decreased from 180 degrees. Thus, unless precautions are taken when either spectrometer is set in the neighborhood of 200 kev, copious coincidences may be observed between the Compton recoil pulses and the backscattered photon peak.

In the measurements in which this phenomenon was considered to be a possible source of error, an effort was made to obviate the effect by placing a lead filter between the source and the crystal in which the high energy gamma-ray was being detected, as indicated in the inset in Fig. 2. For example, a $\frac{1}{8}$-in. lead filter attenuates the 960-kev gamma ray by only about 20 percent but reduces the 200-kev secondary radiation by about 98 percent so that in searching for coincidences between the 960-kev gamma ray and the 206-kev photopeak, spurious coincidences which might be caused by Compton scattering of the 1.17 and 1.26-Mev radiations are greatly reduced.

Results of Coincidence Experiments

The results of the coincidence experiments are summarized in Table III. The letters "*A*", "*B*", and "*X*" represent the combinations where coincidences might be observed if the decay scheme proposed in Fig. 4 is correct. Where no coincidences should appear, and in fact were not observed, the spaces in the table are left blank. For those combinations marked "*A*", coincidences were observed which could be unambiguously interpreted as coincidences between the two transitions indicated. The designation "*B*" indicates that coincidences were in fact observed, but interpretation other than as indicated in the table is possible. The designation "*X*" indicates that coincidences were unobservable because of low intensity or inadequate resolution.

The paragraphs below, indicated numerically in the table, present related experimental details.

Beta-Gamma Coincidence Measurements

(1) The beta-ray spectrum in coincidence with the 873, 960-kev peak is clearly complex. The high-energy component has a half-thickness in *A*1 of from 28 to 30 mg/cm^2, corresponding to a beta ray with a maximum energy of approximately 900 kev. This branch is to be identified with the 0.86-Mev beta ray determined from previous work.[2] The experiment does not permit an accurate estimate of the energy of the other component, but its half-thickness could indicate an energy between 0.4 and 0.6 Mev. This component may reasonably be identified with the 0.52-Mev beta ray. In these experiments, the beta-gamma coincidence distributions for various thicknesses of the aluminum absorbers retained their similarity to the normal distribution in the region of the 873, 960-kev peak, indicating that both of these transitions are in coincidence with the same beta spectrum.

(2) The beta rays in coincidence with the 1.17, 1.26-Mev peak show a half-thickness in aluminum of

18–20 mg/cm^2 corresponding to a beta ray of about 0.6-Mev maximum energy. Within experimental error, this can be identified as the 0.52-Mev beta ray. It is clear from the shape of the coincidence distribution that the 1.17-Mev gamma ray is represented. The statistics of the coincidence measurements are not good enough to establish definitely that the 1.26-Mev radiation is also present, but since it did not stand out as the thicker absorbers were inserted, it seems safe to conclude that it is also fed by the low-energy beta branch. Similar results are obtained for the gamma rays represented in the 298 and 206-kev peaks. In none of these cases did the absorption curve appear to be complex.

(3) The absorption curve for the beta rays in coincidence with the 86.3-kev gamma ray shows an average half-thickness of about 24 mg/cm^2. The curve may be interpreted as an average derived through a mixture of both components, with the lower energy one predominating. Such an interpretation is consistent with the statistics of the experiment.

(The measurement of the beta-ray spectrum carried out earlier at this laboratory indicated the presence of a third component of 396 kev not found present by any of the other investigators. This contradiction, together with the fact that the decay scheme based on the present measurements permits of only two branches, has lead us to conclude that the 396-kev beta ray is not present. The earlier result may be attributable to some unknown instrumental error.)

Gamma-Gamma Coincidence Measurements

(4) When the ten-channel analyzer was set to cover the 90-kev region, coincidences were observed in the vicinity of all other peaks as the single-channel arm of the coincidence circuit was swept across the spectrum. By careful calibration with the 85-kev gamma ray from Tm^{170} and the 94-kev gamma ray from Dy^{165}, these coincidences were found to be primarily associated with the 86-kev transition rather than the 93-kev gamma ray.

To examine more carefully with the ten-channel analyzer the regions of the spectrum in which these coincidences were observed, the single-channel analyzer was adjusted to accept primarily those pulses contained in the 86.3-kev peak. The ten-channel analyzer was set to observe the highest-energy photopeak. It is to be recalled that this peak consists primarily of the photopeak from the 1.17-Mev gamma ray, the 1.26-Mev gamma ray appearing only as a slight broadening of the high-energy side of the distribution (Fig. 1). While the coincidence distribution between this peak and the 86.3-kev peak clearly indicated that the 1.17-Mev gamma ray is in coincidence with the 86.3-kev radiation, the statistics of the experiment are not good enough to conclude that the 1.26-Mev gamma ray is not. While the ten-channel analyzer was still on the high-energy peak, the single channel was moved upward across the remainder of the spectrum and no coincidences were detected with any other radiation.

(5) The $\frac{1}{8}$-in. lead filter was inserted between the source and the ten-channel probe, and the latter set to observe the 873, 960-kev photopeak. The 86.3-kev gamma ray is seen to be predominantly in coincidence with the 873-kev radiation (Fig. 2).

(6) The lead filter was removed and the ten-channel analyzer was adjusted to observe the 200 and 300-kev regions, respectively (the single channel analyzer still set on the 86.3-kev peak). No conclusive change was apparent between the coincidence spectra and the normal distributions. Thus, it could be concluded that the 86.3-kev gamma ray is in cascade with both the 196 and the 215, as well as the 298-kev radiations.

(7) When the single channel was set to accept the intense portion of the 298-kev photopeak, and the 873 and 960-kev pair observed with the ten-channel spectrometer, the coincidence spectrum is seen to be similar to the normal distribution in that region (Fig. 2), indicating that the 298-kev gamma ray is in coincidence with both components of the peak.

(8) The fact that the peak at about 206 kev (Fig. 1) lies between 196 and 215 kev indicates that this peak probably represents both of these radiations. That the 206-kev peak is composed of more than one component is further indicated by the fact that coincidences are observed when the single channel is also accepting pulses in the 200-kev region. The presence of these coincidences not only supports the assumption that the 206-kev peak is comprised of two or more components, the 196 and 215-kev gamma rays, but further that they are in cascade. Using a 10-kev window, several successive observations of the coincidence distribution were made with the single channel set on adjacent energy intervals in the same region. As the channel was advanced upward in energy, the coincidence distribution seemed to shift slightly downward, however, the evidence for this energy shift is not conclusive.

(9) While still observing the 206-kev peak with the ten-channel analyzer, the single channel was moved in successive steps across the 298-kev peak. The coincidence distribution was ascertained for each setting. Analysis of these data showed that most, if not all, of these coincidences were attributable to background effects, and not due to coincidences between the radiations represented in the two peaks. From this it may be concluded that very few, if any, of the 298-kev transitions are in cascade with either the 196- or 215-kev gamma ray.

(10) With the $\frac{1}{8}$-in. lead filter between the source and the single-channel probe, the single-channel analyzer was set with a 50-kev window on the broad 873, 960-kev peak, as indicated by the dotted lines in Fig. 3*A*. Figure 3*B* shows that the coincidence distribution in the neighborhood of the 206-kev peak clearly shifts upward from the normal distribution, in fact, coinciding with the 214-kev calibration peak

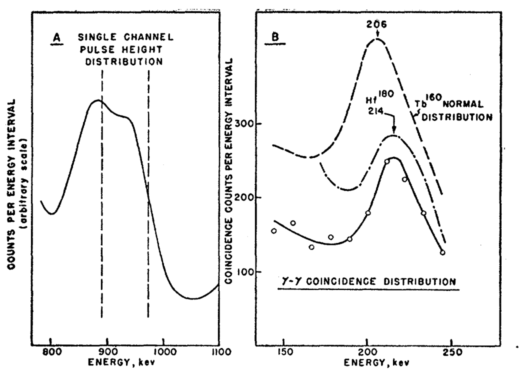

FIG. 3. Coincidence pulse-height distribution for $_{65}Tb^{160}$ (71 day). For the single-channel setting represented in A, the coincidence distribution is plotted in B for the region whose normal distribution is represented by the dashed curve. To aid in estimating the energy represented by the coincidence curve, the normal distribution of $_{72}Hf^{180}$ is also plotted providing a 214-kev calibration peak.

from Hf^{180}. In the corresponding experiment, the single channel was set on the 206-kev peak and the ten-channel on the 873, 960-kev peak with the lead filter between the source and the ten-channel probe. As discussed above, the coincidence distribution is seen to manifest a single peak at about 960 kev (Fig. 2*B-c*). It would thus be concluded that the 215-kev gamma ray is in coincidence with the 960-kev gamma ray. However, as will be seen in the discussion of the decay scheme, the result may better be interpreted as evidence of a transition of about 957 kev which is experimentally indistinguishable from the 960-kev gamma ray.

(11) The search for coincidences between the 759-kev gamma ray and the 206-kev peak was made with the lead filter in place to reduce spurious counts due to Compton scattering of the 873 and 960-kev gamma rays. The single channel was set on the 206-kev peak and the ten-channel analyzer adjusted to where the 759-kev peak (not resolved in the normal spectrum) should appear. The coincidence distribution manifested a peak, but its poorly defined character does not warrant considering it as reliable evidence.

DECAY SCHEME

From the results of the foregoing experiments, the decay scheme proposed in Fig. 4 is deduced as follows:

Consider the two groups of gamma rays, 86.3, 873, 960 kev, and 86.3 kev, 1.17, 1.26 Mev. In each of these groups, the energy of the 86.3-kev transition adds to that of the second gamma ray to be experimentally equal to that of the third. From internal conversion data, the difference between the 873- and the 960-kev transitions is 87 kev, in excellent agreement with the energy measurement of the 86.3-kev transition. Likewise, for the higher-energy pair, the difference between the 1.17- and the 1.26-Mev transitions is about 90 kev, but still equal within experimental error to 86.3 kev. In both cases, the assumption of these groupings is supported by the coincidence measurements, since the 86.3-kev gamma ray is clearly in coincidence with both the 873 and the 1.17-Mev gamma rays (4,5).

Since the 86.3-kev transition is the only element common to these two triads, the association of these five transitions (indicated by heavy lines in the decay scheme) follows logically. It is immediately seen that the energy difference between 960 kev and 1.26 Mev is equal to the 298-kev transition well within experimental limits. Assignment of the 298-kev transition to this position is substantiated by the coincidence measurement which shows the 298-kev gamma ray to be in coincidence with both the 873 and 960-kev as well as the 86.3-kev transition (6,7). Thus, except for the sequential orientation, these six transitions form a closed system which is unique and consistent with both energy differences and coincidence experiments. Without other considerations, one might place either the 298 or the 86.3-kev transition next to the ground state.

The beta-gamma coincidence measurements support the arrangement as shown, considering the 86.3-kev transition as the ground state transition. The conclusion that the highest-energy state in Dy^{160} is 1.26 Mev is supported by the following experiments: (*a*) The scintillation spectrometer detected no pulses of amplitude greater than those to be associated with the high-energy photopeak representing the 1.17 and 1.26-Mev gamma rays. (*b*) No internal conversion lines were detected for any transition of energy greater than 1.26 Mev. (*c*) No gamma rays were found in coincidence with the high-energy peak, except the 86.3 which could definitely be associated with the 1.17-Mev

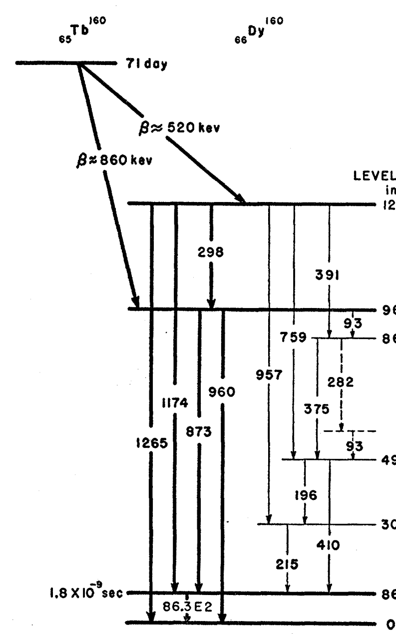

FIG. 4. Proposed decay scheme for $_{65}Tb^{160}$ (71 day).

gamma ray (4). (*d*) The aluminum absorption curve for the beta rays in coincidence with the 1.17, 1.26-Mev peak is simple, showing only the lower-energy component of about 520 kev (2).

The energy difference between the two beta rays, while about 340 kev from the previous measurements of the beta-ray spectrum, is considered close enough to 298 kev to be equal within experimental limits. Thus, these beta-gamma coincidence data, i.e., the 520-kev beta ray in coincidence with the 1.17 and 1.26-Mev gamma rays (2), and the 860-kev beta ray in coincidence with the 873 and 960-kev gamma rays (1) favors placing the 298-kev transition on top with the 86.3-kev at the bottom.

Other considerations favor assigning the 86.3-kev transition to the ground-state position. The 86.3-kev gamma ray is the strongest in the spectrum (Fig. 1) and it also has the most intense internal conversion lines. This indicates that it must be fed by several other transitions, necessitating its being low in the level scheme. From densitometry of the internal conversion lines, the K/L ratio of the transition is 0.9 ± 0.3 indicating that the character of the radiation may be $E2$.[11] This is in confirmation of McGowan's conclusion based on measurements of the K-shell conversion coefficient and of the lifetime of that state; and empirically, ground-state transitions of even-even nuclei are $E2$ transitions. Finally, the energy of 86.3 kev is consistent with that which would be expected from energy systematics of ground-state transitions of even-even nuclei.[12]

The experiments supporting the partial decay scheme just discussed are convincing, but the arrangement disposes of only six of the transitions. If the deductions are correct, and the partial level scheme accepted, then it is readily apparent that there is no way in which the 215-kev transition can be fitted in so that it is in cascade with only the 960- and 86.3-kev transitions. But the experiments do indicate that the 215-kev transition is in coincidence with the 960-kev transition and not the 873 (10). A plausible explanation for this inconsistency is apparent if an energy state is placed at 301 kev, 215 kev above the 86.3-kev level. The coincidences between the 215-kev gamma-ray and what is apparently the 960-kev gamma ray can then be attributed to another radiation of about 957 kev, which represents a transition from the 1.258-Mev level to the 301-kev level. The 957-kev radiation could be strong enough to account for the coincidences without being detected by internal conversion. More evidence for concluding that it is a weak transition is derived from the coincidence experiments between the 298-kev gamma ray and the 873, 960-kev peak (7) (Fig. 2*e*). If the 957-kev radiation were of substantial intensity, the normal distribution might indicate a slightly higher intensity near 960 kev relative to 873 kev than does the coincidence distribution taken with the 298-kev radiation, but no significant difference is apparent. The experiments indicate nothing with respect to the sequence of the 215, 957-kev cascade, but the transition with the lower energy is preferentially placed nearest the ground-state transition.

The coincidence experiments indicate that the 196-kev transition is in cascade with both the 86.3 and the 215-kev radiations (6,8). The presence of the 410-kev transition is taken as evidence that the 196 and 215-kev transitions are adjacent. From these observations, the existence of the level at 497 kev is deduced.

The 759-kev transition is then interpreted as the transition between the 1.258-Mev state and the 497-kev level. The coincidence measurements between the 206-kev peak and the 759-kev region of the spectrum support this arrangement (11), but as has been mentioned, these experiments are not sufficiently unambiguous to be pointed to as primary evidence. The fact that the only beta-ray component found in coincidence with the 206-kev peak was the 520-kev branch does indicate (2), however, that the 196- and 215-kev transitions must be fed predominantly from the 1.258-Mev state, which agrees with the arrangement proposed.

The only reason for placing the 93-kev transition in the position indicated is the energy fit. If it is properly placed here, it must represent a very weak branch, for neither were there any coincidences observed between it and any of the other gamma rays (4), nor were any of the coincidences observed which would support its placement, such as coincidences between the 298-kev and either the 196 or the 215-kev gamma-rays (9). Also, were it a substantial branch, one would expect to find evidence of the high-energy beta-ray branch in coincidence with the 206-kev peak.

The only gamma ray reported by Cork *et al.* which cannot be fitted into the level scheme is the one of 176 kev. We find no evidence for this transition either by internal conversion or by scintillation spectrometer, thus, its association with Tb^{160} is concluded to be doubtful and it is, therefore, disregarded.

We have made an effort to arrive at a decay scheme which is not only consistent with our own data, but which incorporates as much of the previously reported information as possible. Internal conversion lines for the transitions of 282, 375, and 410 kev were not observed in this study, however, more extensive exposures may have led to their detection. The 375- and 410-kev transitions fit into the scheme readily, and the 282-kev transition can be included by placing the 93-kev transition in the alternate position indicated by the dotted lines.

[11] M. Goldhaber and A. Sunyar, Phys. Rev. **83**, 906 (1951).
[12] G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).