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FOREWORD

This group of reprints of papers published in The Physical Review and the Bulletin of the American Physical Society during the year is submitted as a technical report for the year 1956.

The study of nuclear-energy levels is being continued both in the Physics Department of the University and at the Argonne National Laboratory, under their Participating University Program.

J. M. Cork

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I

DECAY OF RADIOACTIVE Ce^{143} (33.4 hr)

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Decay of Radioactive Ce^{143} (33.4 hr)*

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The beta and gamma radiations of Ce^{143} have been studied with a ten-channel scintillation coincidence spectrometer, with a double-focusing magnetic spectrometer, and with photographic magnetic spectrographs. Five beta-ray components and ten gamma rays are identified with the activity, and the decay scheme is established involving six excited states of the daughter Pr^{143} nucleus. It is found that no beta rays of measurable intensity proceed directly to the Pr^{143} ground state. Spin and parity assignments are made for several of the levels.

I. INTRODUCTION

THE 33-hr beta emitter in cerium was first observed by Pool and Kurbatov.[1] Their assignment of the activity to Ce^{143} has been confirmed.[2] Several investigations[3–5] of the conversion- and secondary-electron spectra have been in essential agreement on the existence of gamma rays with energies of about 0.057, 0.29, 0.35, 0.66, and 0.72 Mev. Coincident gamma rays of 0.126 and ~0.16 Mev, for which the 0.29-Mev transition was presumed to be the crossover, were suggested[5] from an early scintillation measurement. Beta-ray components of 1.38, 1.09, and 0.71 Mev, with possible others of lower energy, have been reported.[4,5] Each of these investigators has proposed an essentially different level scheme. In particular, two of them have assumed that the highest energy beta ray proceeds to the ground state of Pr^{143}.

The gamma-ray spectrum has been studied with the ten-channel scintillation coincidence spectrometer at the Argonne Laboratory, using cubical crystals of NaI(Tl) about $2\frac{1}{4}$ in. on a side and Dumont 6292 photomultipliers. The internal-conversion electron spectrum has been observed with photographic magnetic spectrographs both at Argonne and at the University of Michigan. The beta-ray spectrum has been analyzed with the double-focusing magnetic spectrometer at the University of Michigan. In addition, the beta-ray spectra in coincidence with various gamma rays have been observed with the scintillation spectrometer, using an anthracene crystal and an RCA 5819 photomultiplier.

Sources were prepared by neutron irradiation of cerium oxide enriched in mass 142 in the Argonne reactor, CP-5. A number of different irradiations ranging up to 37 hours were performed.

II. GAMMA-RAY SPECTRUM

Figure 1 shows the NaI(Tl) pulse-height distribution obtained with a freshly irradiated source in "good" geometry. As shown in the insert, a lead collimator 4 inches long is used, having a tapered aperture that defines a cone limited to the central part of the crystal. A 1-cm thick slab of Lucite in front of the crystal serves to absorb all beta rays and conversion electrons. The whole assembly is enclosed in a 2-inch thick lead shield. The superimposed Cs^{137} spectrum illustrates the spectrum of a single gamma ray in this geometry.

The decay of the spectrum was observed in this geometry over a period of 12 days. All of the peaks were found to decay with the 33-hr period except for the initially small peak at 0.145 Mev and part of the x-ray peak. These can be attributed to the well-known[6] single gamma ray of Ce^{141} (33.1-day).

Evident in the figure are "photopeaks" for five of the previously reported gamma rays, as well as several additional peaks. The peak at 0.493 Mev is seen, by comparison with the superimposed Cs^{137} spectrum, to be much too sharp to be due to the Compton distributions of higher energy gamma rays. This and the peaks labeled 0.232 and 0.861 Mev are confirmed to be gamma rays by observation of their conversion lines. The last peak, at 1.10 Mev is not at the right energy for any expected "sum peak" (very unlikely in this geometry), and therefore represents another gamma ray. One additional weak gamma ray at 0.565 Mev will be shown to exist in the discussion of coincidence spectra. No evidence is found for gamma rays of 0.126 or 0.16 Mev.

The gamma rays are listed in Table I together with their associated conversion-electron lines where observed. The energy values quoted are based on the conversion data in most cases. In no case is this value in conflict with the scintillation data. The scintillation spectrometer is calibrated, for the two gamma rays not observed in conversion spectra, with the gamma rays of Cs^{137} and Co^{60}. No definite evidence is found in the conversion spectra for any transition not observed by scintillation.

A photometric measurement from the spectrograph plates of the K/L ratio proved to be feasible only for the 0.294-Mev transition, for which the value 6.1 ± 0.6 is obtained. The lines associated with the 0.0574-Mev

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[1] M. L. Pool and J. D. Kurbatov, Phys. Rev. **63**, 463 (1943).
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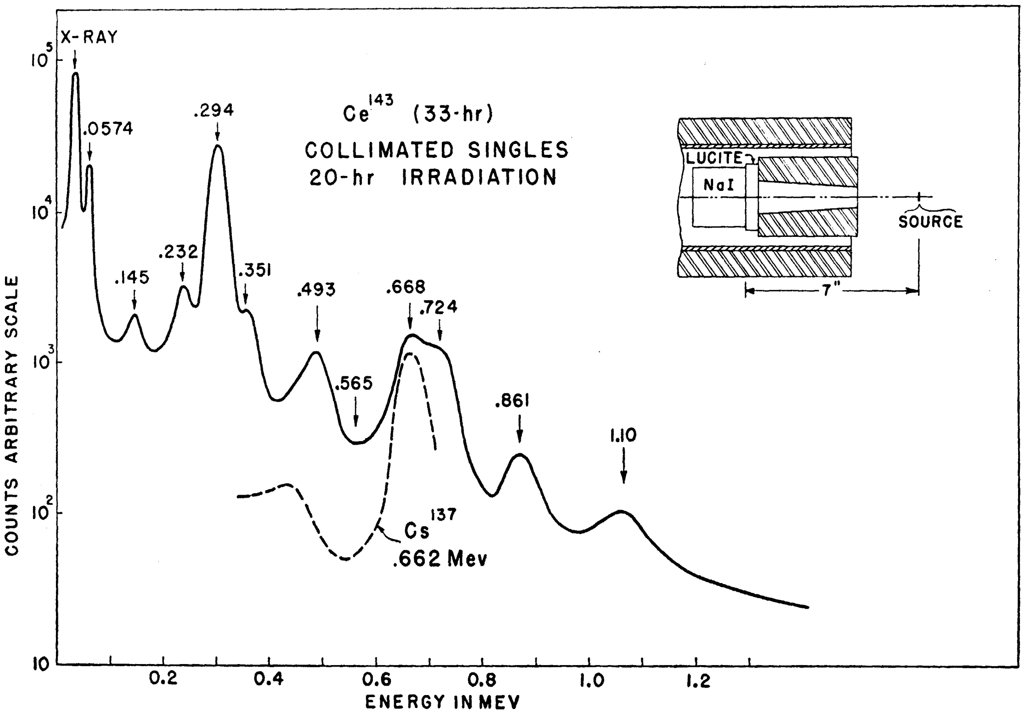

FIG. 1. NaI(Tl) normal pulse-height distribution of Ce^{143} (33.4-hr) in "good" geometry. The geometrical arrangement is illustrated in the insert. The dashed curve is a portion of the pulse distribution of the single gamma ray (0.662 Mev) of Cs^{137} in the same geometry.

transition are actually very intense, but the sensitivity of the photographic emulsion varies rapidly with energy at low energies and causes some uncertainty. Estimates of the K/L ratio led to interpretations in conflict with other data. Only a single rather well-defined L-line is observed for the 0.0574-Mev transition, even though M- and N-lines are readily seen, and it appears definitely to be the $L_{\rm I}$ subshell line. The implications of this fact for interpretation of the transition character will be shown to be consistent with other data.

TABLE I. Gamma-ray and conversion-line energies in Mev.

Gamma energy	Conversion-line energy	Interpretation	Energy sum
0.0574±0.0002	0.0154	K	0.0574
	0.0505	$L_{\rm I}$	0.0575
	0.0560	M	0.0574
	0.0572	N	0.0576
0.1416±0.0003	0.1036	K	0.1416
(Ce^{141})	0.1391	$L_{\rm II}$	0.1415
0.232 ±0.001	0.1900	K	0.2320
	0.2245	$L_{\rm I}$	0.2314
0.294 ±0.001	0.2522	K	0.2942
	0.287	L	0.294
	0.293	M	0.294
0.351 ±0.001	0.309	K	0.351
0.493 ±0.002	0.451	K	0.493
	0.48	L	0.49
0.565 ±0.005	None		
0.668 ±0.002	0.626	K	0.668
0.722 ±0.002	0.682	K	0.722
0.861 ±0.005	0.819	K	0.861
1.10 ±0.01	None		

For the gamma-gamma coincidence experiments, the source was placed between two identical NaI crystals, which were about $\frac{1}{2}$ inch apart. 900 mg/cm^2 of Al was placed in front of each counter to absorb the beta rays. Pulses from one of the counters were selected with a single-channel differential analyzer and used to gate the ten-channel analyzer. As no "fast" coincidence channel was employed, the coincidence resolving time was 2×10^{-6} second. Rather low counting rates were used, however, so that random coincidences were always negligible. In certain of the experiments, where one counter was observing low-energy events, and the other high-energy events, 4 g/cm^2 of lead was placed in front of the high-energy counter to intercept low-energy quanta scattering back to the low-energy counter.

Curve B in Fig. 2 shows the spectrum of coincidence pulses observed when the gating channel was set on the 0.0574-Mev peak. Curve A is the ungated spectrum for the same geometry, and Curve C is the difference between A and B for energies greater than 0.1 Mev. The situation of the 0.0574-Mev peak in the total spectrum (see Curve A) is such that the gating channel is often actuated by pulses from the intense Pr x-ray peak at 0.036 Mev. These x-rays arise from internal conversion of all of the various gamma rays, and could therefore

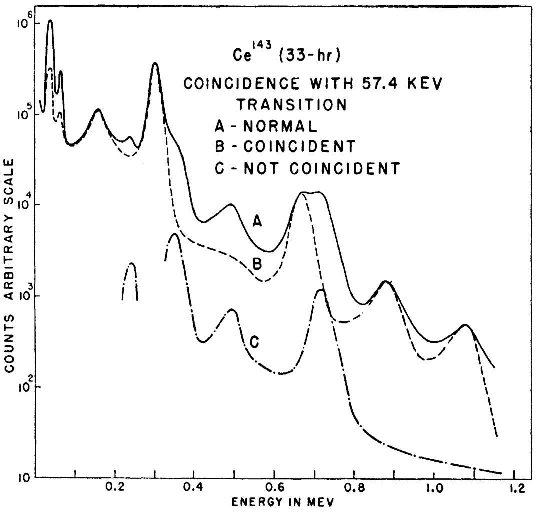

FIG. 2. NaI(Tl) pulse-height distributions of Ce^{143} in coincidence geometry (see text). *A*. Ungated spectrum. *B*. Coincidence spectrum gated by the 0.0574-Mev peak. *C*. Difference between *A* and *B*.

give rise to peaks in the coincidence spectrum that are not in coincidence with the 0.0574-Mev transition. This is undoubtedly the explanation for the x-ray and 0.0574-Mev peaks in the coincidence spectrum. However, it is found in other experiments (see below) that, of all the appreciably converted strong transitions (other than the 0.0574-Mev transition itself), none is strongly coincident with anything of energy greater than 0.1 Mev. Thus, virtually all coincidence pulses above this energy must really be coincident with either the gamma quantum or the conversion x-ray of a 0.0574-Mev transition.

To verify these suppositions, the coincidence spectrum was observed with the gating channel moved from the 0.0574-Mev peak to the x-ray peak. As expected, no changes were apparent in the region above 0.1 Mev.

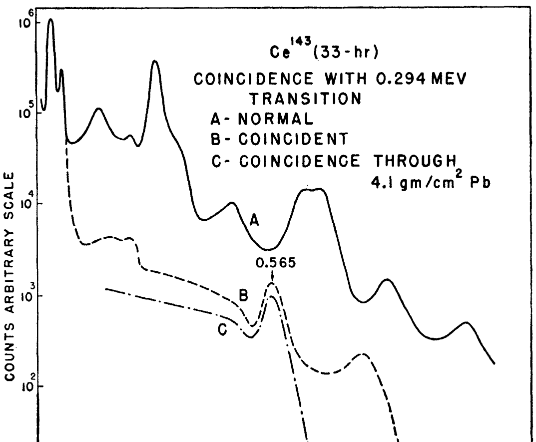

FIG. 3. NaI(Tl) pulse-height distributions of Ce^{143} in coincidence geometry (see text). *A*. Ungated spectrum. *B*. Coincidence spectrum gated by the 0.294-Mev peak. *C*. Same as *B*, through 4.1 g/cm² of Pb.

The spectra of Fig. 2 suggest that there exists a low-lying state at 0.0574 Mev in the Pr^{143} nucleus, to which all gamma rays in the decay lead except the four of energies 0.232, 0.351, 0.493, and 0.722 Mev. Of these, the 0.351- and 0.722-Mev gamma rays appear from their energies to be crossovers for 0.294–0.0574 and 0.681–0.0574 cascades, respectively. These assumptions are consistent with all other data.

Curve *B* in Fig. 3 is the spectrum of pulses in coincidence with the 0.294-Mev peak. To determine whether the peaks at 0.565 and 0.81 Mev are gamma rays or merely represent Compton scattering of higher energy gamma rays coincident with backscattered quanta of 0.29 Mev, various thicknesses of Pb were placed in front of the counter. The 0.565-Mev coincidence peak was attenuated by amounts characteristic of about 0.55 Mev and therefore represents a gamma ray, while the 0.81-Mev peak showed attenuations appropriate to 0.3 Mev and is thus due to backscattering. The upper portion of the spectrum as it appears through 4.1 g/cm² of Pb is shown as Curve *C* in Fig. 3.

TABLE II. Summary of gamma-gamma coincidence data. *X*: Coincidences observed; 0: coincidences not observed.

Gamma-ray energy in Mev	Gamma-ray energy in Mev								
	1.10	0.861	0.722	0.668	0.565	0.493	0.351	0.294	0.232
0.0574	*X*	*X*	0	*X*	?	0	0	*X*	0
0.232	0	0	0	0	...	*X*	...	0	
0.294	0	0	0	0	*X*	0	0		
0.351	0	0	0	0	...	...			
0.493	0	0	0	0	...				
0.565	0	0	0	0					
0.668	0	0	0						
0.722	0	0							
0.861	0								

Virtually all x-rays coincident with the 0.294-Mev peak must arise from internal conversion of the 0.0574-Mev transition. Therefore, comparison of the areas of the x-ray and 0.0574-Mev peaks in this coincidence spectrum provides a direct measurement of the *K*-shell internal-conversion coefficient of the latter transition. The absorption efficiency of the crystal is 100% for both peaks, but corrections must be made for the fluorescent yield of Pr, the relative fractions of iodine *K* x-ray escapes, and the relative attenuations by beta absorbers and light shields. The value obtained is $\alpha_K = 5.9$, with an estimated uncertainty of less than ten percent.

In further experiments, the 0.232- and 0.493-Mev peaks are found to be in coincidence. None of the four peaks above 0.6 Mev are observed in a coincidence distribution in which the gating channel is set to accept all pulses corresponding to energies above 0.1 Mev. Table II summarizes the gamma-gamma coincidence data. An *X* indicates that coincidences are observed, while a 0 indicates that coincidences were sought and definitely not observed. Experiments that were not done are shown as ··· in the table. The 0.565-Mev peak was too weak to be seen in either the normal or 0.0574-Mev coincidence spectra, so a question mark is shown.

III. BETA-RAY SPECTRUM

Previous reports[4,5] on the beta spectrum listed only three resolved components, but suggested the probable existence of other lower-energy branches. The newly discovered gamma rays, together with facts about the level scheme deduced from the coincidence measurements, indicated that there must be two more components. A successful attempt to resolve them was made with the magnetic double-focusing spectrometer at the University of Michigan.

Analysis of the spectrum is complicated by the presence of longer lived low-energy components due to

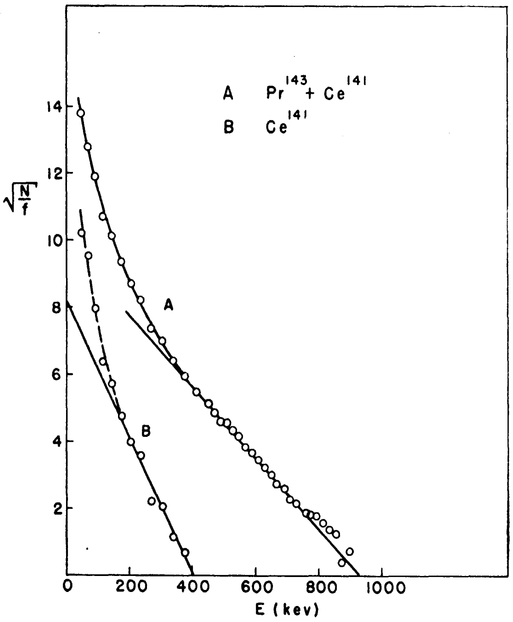

FIG. 4. Kurie plots of residual beta spectrum of Pr^{143} and Ce^{141} components after decay of Ce^{143}. *A*. Composite spectrum. *B*. Remainder after subtraction of Pr^{143}.

the daughter product Pr^{143} and also Ce^{141}, the latter representing initially about 2% of the activity. The spectrum had to be remeasured after the Ce^{143} had died out, to determine the contributions of these activities to the counting rates in the initial study. Total activity of the sources was followed with an ionization chamber, and the results obtained over a 32-day period indicate half-lives of 33.4 hours and 13.95 days for Ce^{143} and Pr^{143} respectively. The half-life of Ce^{141} was taken to be the previously reported[6] 33.1 days, which was not verified here.

The source, which had been irradiated for 37 hours, was mounted on a narrow strip of cellulose tape. The G-M counter was equipped with a Zapon window about 15 micrograms per square centimeter in thickness. The initial run of the spectrum was begun about 24 hours after the end of the irradiation, and covered a period of

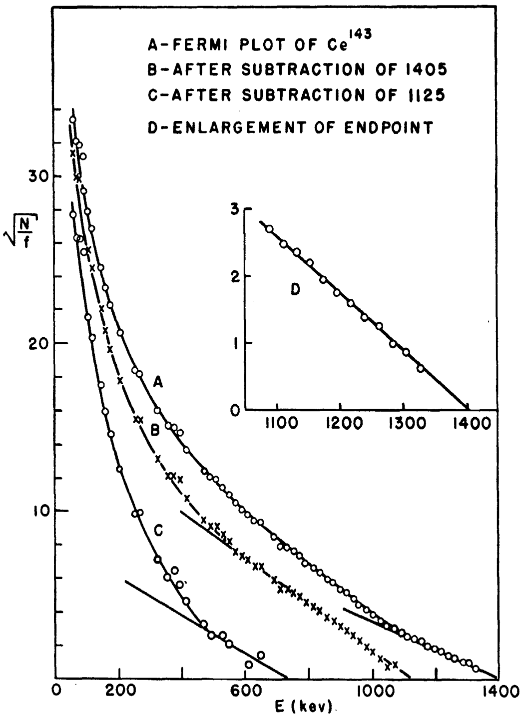

FIG. 5. Kurie plots of Ce^{143} beta spectrum. *A*. Total composite spectrum. *B*. Remainder after subtraction of 1.40-Mev component. *C*. Remainder after further subtraction of 1.125-Mev component. *D*. Enlargement of end-point region of *A*.

three days. The second run was begun seventeen days later, and required thirteen days to complete because of the very low counting rates.

In order to make proper corrections for the long-lived components, the residual composite spectrum of the second run was resolved into its Pr^{143} and Ce^{141} components. A Kurie plot using the Fermi functions and half-life characteristic of the Pr^{143} decay yields a straight line with an end point of 0.93±0.01 Mev for the highest-energy component (see Fig. 4). The Kurie plot for the remainder, using the Fermi functions and half-life for Ce^{141}, is also shown in Fig. 4. Although the plot suggests only a single component (except for considerable upward deviation below 150 kev), the data are not inconsistent with the reported[6] two components of Ce^{141}. They are not resolved here because of the very low counting rates associated with this activity in the source.

The Pr^{143} and Ce^{141} spectra were corrected for decay and subtracted from the original data of the first run, after which the remainder was corrected for the 33.4-hr decay of Ce^{143}. The Kurie plot is shown in Fig. 5 with the numerous internal-conversion lines at low energies omitted.

In analysis of this complex Kurie plot, an allowed shape is assumed for all components. This is consistent with the log *ft* values eventually determined, and with the appearance of each component in the plot. However, only the high-energy end of each one is seen because of the complexity of the spectrum. All straight-line fits are made by the method of least squares. The plot is re-

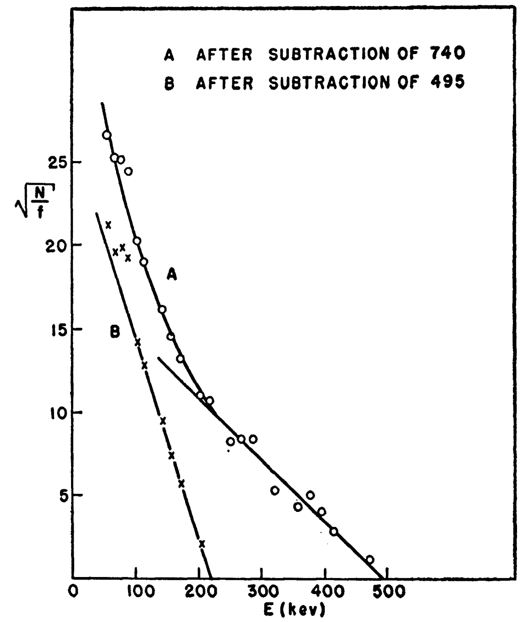

FIG. 6. Kurie plots of the two lowest energy beta components of Ce^{143}. *A*. Remainder after subtraction of 1.40-, 1.125-, and 0.74-Mev components. *B*. Remainder after further subtraction of 0.50-Mev component.

solved into five components, as shown in Figs. 5 and 6 and listed in Table III. After subtraction of the first two components, the plot was a little ambiguous, and further analysis is based in part on independent information that there is a component of around 0.7 Mev in coincidence with gamma radiation (see below). The fact that points below 0.1 Mev still lie somewhat above the last straight line can probably be attributed to backscattering in the source. The errors quoted in Table III represent the statistical uncertainties in the least-squares fit. In the case of the lowest-energy component, the calculated statistical error was very small and was not believed to be significant after so many subtractions.

A semiquantitative measurement of the beta rays in coincidence with various gamma rays was made with the scintillation spectrometer. The beta rays were detected with an anthracene crystal $\frac{3}{16}$ inch thick and $1\frac{1}{2}$ inches in diameter, coupled to an RCA 5819 photomultiplier. The pulse spectrum was examined with the ten-channel analyzer, gated by a NaI(Tl) gamma-ray counter and single-channel analyzer. The source, on a cellulose tape backing, was placed between the two closely spaced counters and 900 mg/cm² of Al covered the gamma counter as a beta shield. An Al foil of about 5 mg/cm² thickness covered the beta counter as a light shield.

An energy calibration and an indication of the performance of the spectrometer were obtained by examining the beta spectrum and the conversion line of Cs^{137}, shown in the insert on Fig. 7. The beta spectrum is seen to display a rather long straight section that extrapolates to zero at approximately the expected end point, despite the fact that the curve trails off far beyond this end point. It appears from this, and is consistent with other experience, that spectra from this counter can give rough estimates of end-point energies without correction for resolution, scattering, etc. No attempt is made to deduce Kurie plots from these data.

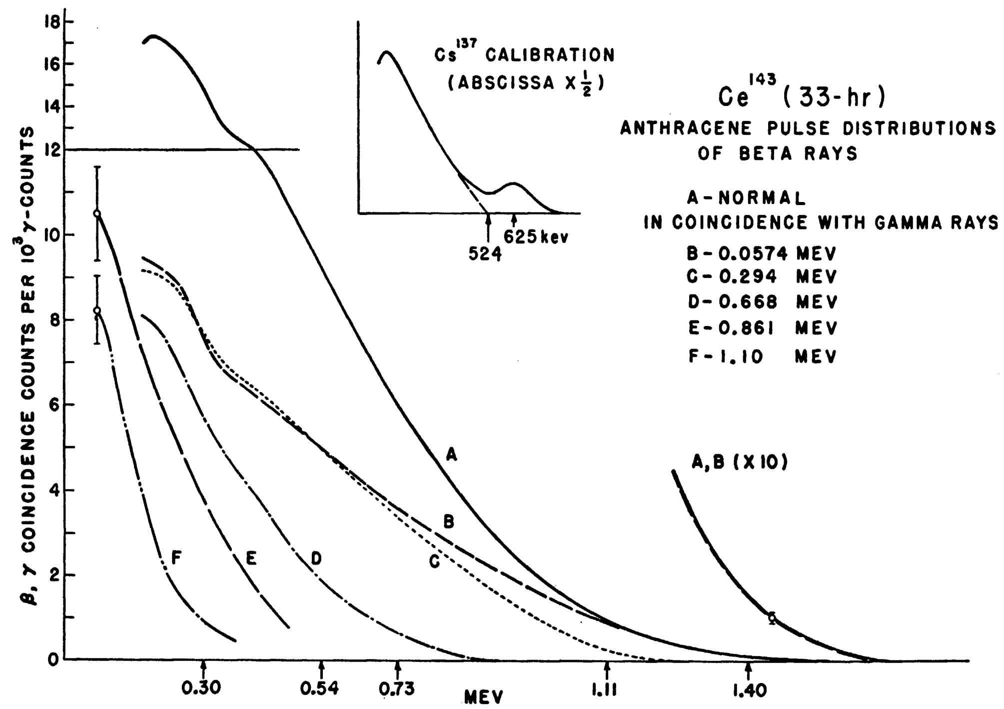

FIG. 7. Anthracene pulse-height distributions of the beta rays of Ce^{143}. *A*. Normal or ungated spectrum. *B–F*. Coincidence spectra gated by gamma-ray pulses of energies: *B*. 0.0574 Mev; *C*. 0.294 Mev; *D*. 0.668 Mev; *E*. 0.861 Mev; *F*. 1.10 Mev. Insert shows the spectrum of Cs^{137} in the same geometry (abscissa$\times\frac{1}{2}$). All curves normalized as coincidence counts per gamma count.

Curve A of Fig. 7 is the ungated scintillation beta spectrum of Ce^{143}, while curves B, C, D, E, and F are the spectra in coincidence with the gamma-ray peaks of 0.0574, 0.294, 0.668, 0.861, and 1.10 Mev, respectively. The arrows indicating end points are placed in accordance with the Cs^{137} calibration. For the first three components, the indicated end point is at the energy determined by the magnetic spectrometer measurements, while for the last two they are placed at somewhat higher energies as expected from the gamma-ray energies.

It is evident that there really are five distinct components, and that each is consistent (within the very considerable uncertainties) with one of the expected end points and the above extrapolation criterion. The disagreement in the energies of the two lowest-energy components between the magnetic spectrometer measurements and the gamma-ray measurements cannot be resolved from the scintillation spectra. Counting statistics are indicated for a few representative points in Fig. 7, and are seen to be very poor for the low-energy components despite counting times of several hours.

Each component is seen without the presence of any higher energy components so that no subtractions were required. This is due to the very fortunate circumstance that if a given beta ray and gamma ray are in coincidence, all higher-energy beta rays are coincident only with lower energy gamma rays. Some slight gamma-gamma background is indicated in the last two curves, E and F, but is entirely negligible in all the others.

TABLE III. Summary of the magnetic spectrometer measurements of the beta rays.

Isotope	Beta-energy (Mev)	Intensity (%)	Logft	Spin change	Parity change
Ce^{143}	1.40 ±0.02	37	7.75	0,1	yes
Ce^{143}	1.125±0.015	40	7.30	0,1	yes
Ce^{143}	0.74 ±0.15	5	7.7	0,1	yes
Ce^{143}	0.50 ±0.03	12	6.6	0,1	yes
Ce^{143}	~0.22	6	5.8	0,1	yes or no
Pr^{143}	0.93 ±0.01	100	7.60	0,1	yes

The normal and 0.0574-Mev coincidence distributions (Curves A and B) merge together above the end of the next lower component (Curve C). Careful examination of this region of the spectrum with good statistics shows no detectable differences. The 1.40-Mev component evidently proceeds to the 0.0574-Mev level, and it can be asserted that there is no slightly higher energy branching to the ground state of intensity more than a few percent of the 1.40-Mev branch.

In one further coincidence experiment, the gamma-ray spectrometer was gated by the beta counter. The behavior of various gamma-ray peaks was observed as the coincident beta rays were attenuated with aluminum absorbers. In every case the coincidence rates were observed to fall off with half-thicknesses of Al consistent with other measurements of the beta-ray energies. Of particular interest were the not-fully-resolved gamma-ray pairs 0.294–0.351 and 0.668–0.722 Mev. In each case the compound peak was observed to absorb out without change of shape, indicating that its two component gamma rays originate from the same level.

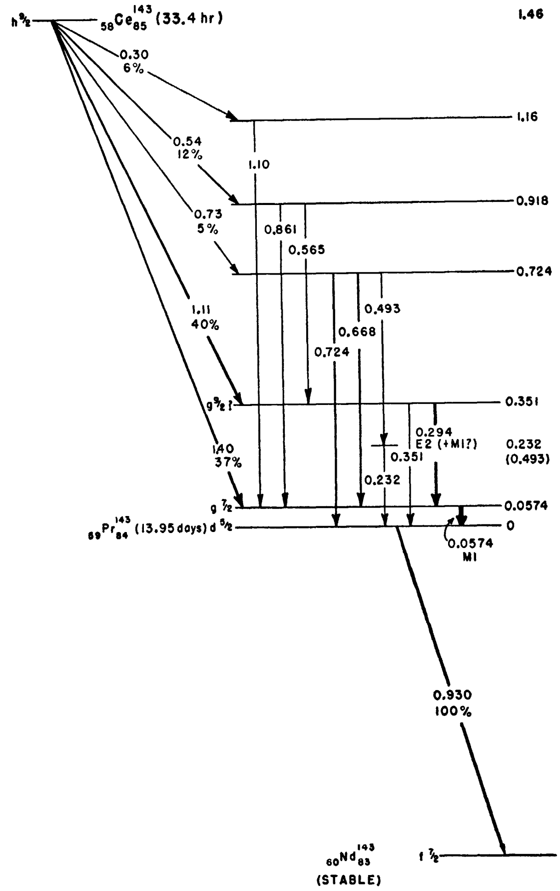

FIG. 8. The decay scheme of Ce^{143} (33.4-hr).

IV. CONCLUSION

The given data all support the decay scheme shown in Fig. 8. There is some inconsistency concerning the energy of the lowest energy beta-ray component, in that the gamma-ray energies require that the beta ray have an energy of 0.30 Mev, while the magnetic spectrometer analysis indicated a value of 0.22 Mev. The discrepancy is not regarded as serious since the accumulated errors of the many subtractions in the latter analysis must be very considerable. The energy of the 1.10-Mev gamma ray, on the other hand, was measured with reference to the 1.17-Mev line of Co^{60}, and is believed to lie within the quoted uncertainty.

The relative order of the 0.493–0.232 Mev cascade was not determined in this study. The excellent agreement of this energy sum with the 0.722-Mev gamma ray leaves little doubt that the cascade does come from this level, however. No other position would be consistent with the gamma-gamma coincidence data.

The value of the K-conversion coefficient (5.9), the predominance of the L_I subshell line in the L-conversion, and the lifetime (less than the resolving time of the coincidence circuit, 2×10^{-6} second) of the 0.0574-Mev transition are all consistent with an $M1$ interpretation. Lack of exact theoretical values for α_K does not permit exclusion of some $E2$ admixture, but the lack of an observable L_{II} conversion line limits this possibility to a few percent.

The measured K/L ratio of the 0.294-Mev transition indicates several possibilities. $M3$ can be excluded because the life of this state is also less than the resolving time of the coincidence circuit. $M2$ or $E1$ interpretations are inconsistent with the plus parity of the 0.351-Mev state indicated by the beta-ray measurements. The remaining choice is $E2$.

According to the single-particle model, the ground state of Pr^{143} (59 neutrons) may be $d_{5/2}$ or $g_{7/2}$. Either assignment is consistent with the observed character of the beta transition to Nd^{143}, which has a measured spin[6] of 7/2 and is $f_{7/2}$ (83 neutrons). The ground state of Ce^{143} (85 neutrons) may be $f_{7/2}$ or $h_{9/2}$. The $f_{7/2}$ assignment is unsatisfactory since the state could then undergo a first-forbidden beta transition equally well to either of the possible choices for the ground state of Pr^{143}, whereas the ground-state transition is not observed. If it were $h_{9/2}$, however, decay to a $g_{7/2}$ state in Pr is only first forbidden, but decay to a $d_{5/2}$ state is "l-forbidden" with $\Delta l=3$. This assignment is therefore consistent with observation, if the Pr^{143} ground state is identified as $d_{5/2}$. Then the 0.0574-Mev excited level can be $g_{7/2}$, consistent with the $M1$ character of the gamma transition.

Although it is indicated above that the 0.294-Mev transition appears to be $E2$, the fact that the 0.351-Mev crossover is seen makes it seem unlikely that the 0.351-Mev level has a spin as great as 11/2. It is tentatively suggested that this is a $g_{9/2}$ state, and that there may be some $M1$ admixture in the 0.294-Mev transition.

V. ACKNOWLEDGMENTS

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II

RADIATIONS FROM THE ACTIVE ISOTOPES OF YTTERBIUM

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Radiations from the Active Isotopes of Ytterbium*

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By using Yb of high purity (99.8%) irradiated in the maximum flux of the Argonne pile and studied by scintillation and magnetic photographic spectrometers, a reevaluation of the energies of the radiations has been made. Several previously unreported gamma rays are found and nuclear level schemes for Tm^{169}, Lu^{175}, and Lu^{177} are proposed. Several of the levels appear to be rotational states in the unified nuclear model. Yb^{169} decays with a half-life of 30.6 days by K capture, followed by eleven gamma rays in Tm^{169}. Rotational levels lie at 8.4, 118.3, and 139.1 kev. The gamma energies are 8.4, 20.6, 63.2, 93.6, 109.9, 118.3, 130.7, 177.7, 198.6, 261.0, and 308.3 kev. Yb^{175} decays with a half-life of 4.2 days by β emission (471 kev max) followed by five gamma rays in Lu^{175}. Rotational levels exist at 114.1, and 251.9 kev. The gamma energies are 114.1, 137.8, 145.0, 282.9, and 397.0 kev. Yb^{177} decays with a half-life of 1.88 hour by β emission followed by gamma transitions in Lu^{177}. In addition to any lower energy gamma rays, two high-energy transitions are found at 1.080 and 1.228 Mev. The latter is a cross over for the 1.080- and 0.148-Mev gammas which are in coincidence. The expected well-known daughter product Lu^{177}, if present at all, is too weak to be observed by the magnetic spectrometers.

YTTERBIUM exists in nature as seven stable isotopes, with masses ranging from 168 up to 176, except for 169 and 175. Neutron capture might be expected to produce radioactive Yb^{169}, Yb^{175}, and Yb^{177}. Previous studies have been made[1–3] on these activities with some disagreement in reported results. Since Yb samples of high purity (99.8%) are now available and the neutron flux density in the pile is much greater than was used in the earlier irradiations, a reinvestigation of the radioactivities seemed worthwhile.

Specimens were irradiated in the maximum flux region of the Argonne pile and were studied in both magnetic photographic and scintillation spectrometers. The beta spectrum of Yb^{175} was observed in the double-focusing magnetic spectrometer. Studies of the short-lived (1.88 hour) activity were made on spectrometers located adjacent to the pile.

TABLE I. Conversion electron energies due to transitions in Tm (Auger lines omitted) in kev.

Electron energy	Interpretation	Energy sum	Electron energy	Interpretation	Energy sum
6.1	M	8.4	101.1	L_3	109.8
7.9	N	8.4	107.5	M	109.8
10.5	L_1	20.6	108.7	L_2	118.3
18.3	M	20.6	109.5	N	110.0
20.3	N	20.8	118.3	K	177.7
34.2	K	93.6	120.4	L_1	130.5
50.5	K	109.9	120.9	L_2	130.5
53.0	L_1	63.1	121.9	L_3	130.6
53.5	L_2	63.1	128.6	M	130.9
54.5	L_3	63.2	130.4	N	130.9
58.9	K	118.3	139.4	K	198.8
60.9	M	63.2	167.6	L_1	177.7
62.7	N	63.2	175.2	M	177.5
71.3	K	130.7	176.9	N	177.4
83.6	L_1	93.7	188.4	L	198.5
83.9	L_2	93.5	196.0	M	198.3
84.7	L_3	93.4	198.0	N	198.5
91.3	M	93.6	201.6	K	261.0
93.1	N	93.6	248.7	K	308.1
99.9	L_1	110.0	298.2	L_1	308.3
100.2	L_2	109.8	306.4	M	308.7

Due to the very great source strength, spectrograms could be obtained with exposures of a few hours, with excellent geometry. Some sixty electron conversion lines were observed and measured. The electron lines appeared to belong to two distinct groups as judged by their half-lives and their K–L–M energy fits. One group satisfying the work functions of Tm ($Z=69$) decayed with a half-life of 30.6 days. These transitions are believed to occur in Tm^{169} following K capture in Yb^{169}. Since Yb^{168} is not abundant (0.14%) in normal Yb, it must have a very large capture cross section to produce the high yield of Yb^{169}. The energies of the electron lines that decay with the 30.6-day half-life, exclusive of those of Auger origin, are presented in Table I. The interpretation of these lines confirms the existence of eleven gamma rays. Certain of these (8.4 and 261 kev) had not been observed before. Some gamma rays previously reported[3] could not be found, particularly those of energy 142.6 and 160 kev. Conversion lines attributed to these gamma energies are otherwise interpreted.

Table II shows the energies of the gamma rays together with their K/L ratios and the relative intensities of the L lines, where observable. The no-screen photographic emulsion appears able to record energies as low as 5 kev. The lowest energy gamma ray (8.4 kev), which is of considerable theoretical interest, can energetically yield on conversion only M and N electrons. These observed electron lines at 6.1 and 7.9 kev are believed to be not of Auger origin because of their sharpness. The relative intensities of many of the electron lines were determined from microphotometer traces of the photographic plates. Corrections were made for varying radius and emulsion sensitivity with energy. In some cases only a visual estimate could be made of the relative intensities.

* This work was supported jointly by the Office of Naval Research and the U. S. Atomic Energy Commission.

1 Cork, Keller, Rutledge, and Stoddard, Phys. Rev. 78, 95 (1950).
2 A. Sunyar and J. Mihelich, Phys. Rev. 81, 300 (1951).
3 Martin, Jensen, Hughes, and Nichols, Phys. Rev. 82, 579 (1951).

Since most of the gamma rays enter into coincidence with others, and with Tm x-rays, the lifetimes of all unstable levels must be short. A comparison of the observed line intensities with the calculated internal conversion coefficients of Rose *et al.*[4] for the K, L_1, and L_2 shells and with the relative conversion coefficients for the L_3 subshell given[5] by Church and Monahan, makes possible an assignment of multipolarities for most of the gamma rays. Where the ratio of intensities for the L lines was not supported by the K/L ratio, in making an assignment of multipolarity, less weight was given to the latter because of the large and somewhat uncertain variation in emulsion sensitivity with energy. The preferred assignments of multipolarity are shown in column 6 of Table II. It appears in several cases that the observed intensities can best be satisfied by a mixture of $M1$ and $E2$ radiations, although for the 63.2-, 93.6-, and 109.9-kev transitions the possibility of an $E1$ assignment cannot be eliminated on the basis of the relative line intensities alone.

TABLE II. Gamma energies in Tm^{169} with intensities and multipolarities. (The symbol x indicates that only one L line was observed.)

Gamma energy kev	K/L	Rel. intensity L_1	L_2	L_3	Multipolarity
8.4					
20.6		x			$M1$
63.2		10	4.3	5.5	$M1$, $E2$
93.6	1.6±0.2	10	1.8	1.0	$M1$, $E2$
109.9	2.9±0.3	10	1.9	0.6	$M1$, $E2$
118.3	0.9±0.3		x		$E2$
130.7	0.8±0.2	[10]		9	$E2$
177.7	5.6±0.2	x			$M1$, $E2$
198.6	6.6±0.2	x			$M1$, $E2$
261.0					
308.3	3.5±0.2	[x]			$E2$

Although the resolution of the scintillation spectrometer is not comparable with that of the magnetic instruments, important information on coincidences and summations was obtained with it. A single crystal yields the distribution shown in Curve A of Fig. 1, indicating six peaks, some of which are composite. A coincidence curve with thulium x-rays (50 kev) is identical in shape with the singles curve. A similar result is obtained with the fixed channel set on 20 kev. Since there exists the possibility of back-scattered iodine x-rays (29 kev) from the crystal and the subsequent escape peaks of the thulium x-rays, the above similarity in results is not unexpected. The high-energy side of the 115-kev peak (130.7) was found to be in coincidence with the low-energy side of the 190-kev peak (177.7). The 261-kev peak was in coincidence with the 110 or 118 or both but not with the peaks at 130, 190,

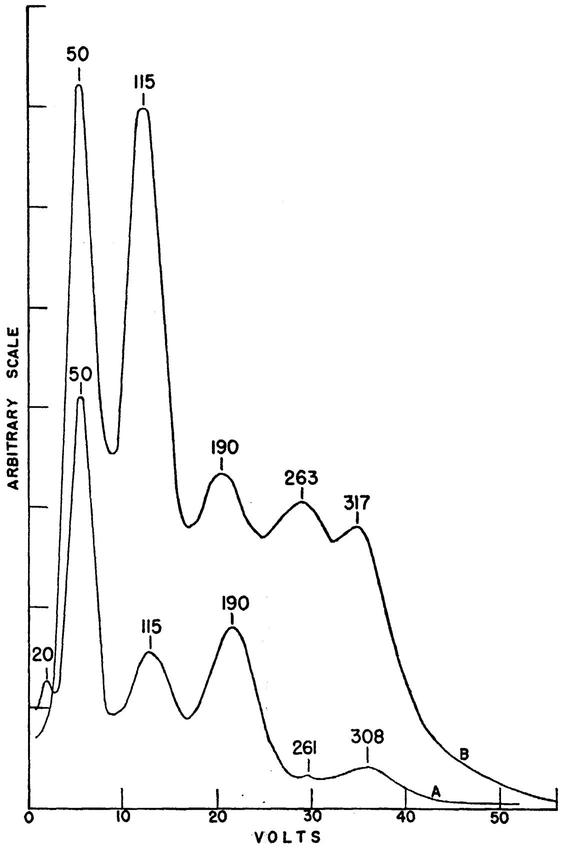

FIG. 1. Scintillation spectrometer peaks; A—singles, B—source in crystal well. (Energies in kev.)

261, or 308 kev. With good geometry the 308-kev peak is found in coincidence only with the 50-kev peak. On the other hand, with 2π solid angle a coincidence peak appears at 115 kev which is attributed to summations between thulium x-rays and the 63-kev gamma. When the source was placed in a narrow well in the NaI crystal so as to give summation effects, the 20-kev peak disappeared and the 50- and 190-kev peaks were lessened in height while those at 115, 261, and 308 kev were augmented as shown in Curve B, Fig. 1.

A nuclear level scheme for Tm^{169} is presented in Fig. 2. The spin of the ground state for the odd-A ($Z=69$, $N=100$) nucleus has been measured to be 1/2. This is interpreted from the shell model as an $s_{\frac{1}{2}}$ state. Some calculations of the low-energy gamma rays to be expected in Tm^{169}, assuming them to be transitions between rotational states in the unified nuclear model, have been made by Mottelson and Nilsson.[6] Their expression for the energy E_I in terms of the spin I is

$$E_I=(\hbar^2/2J)\{I(I+1)+a(-1)^{I+\frac{1}{2}}(I+\tfrac{1}{2})\},$$

where J is the moment of inertia and a is a constant as I takes values 1/2, 3/2, 5/2, 7/2, 9/2, etc. Using the values for the low-energy gammas reported[3] by Jensen *et al.*, which are somewhat in error, they derived a value

[4] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report No. ORNL-1023, 1951 (unpublished); and subsequent letters.

[5] E. L. Church and J. E. Monahan, Phys. Rev. **98**, 718 (1955).

[6] B. R. Mottelson and S. G. Nilsson, Z. Physik **141**, 217 (1955).

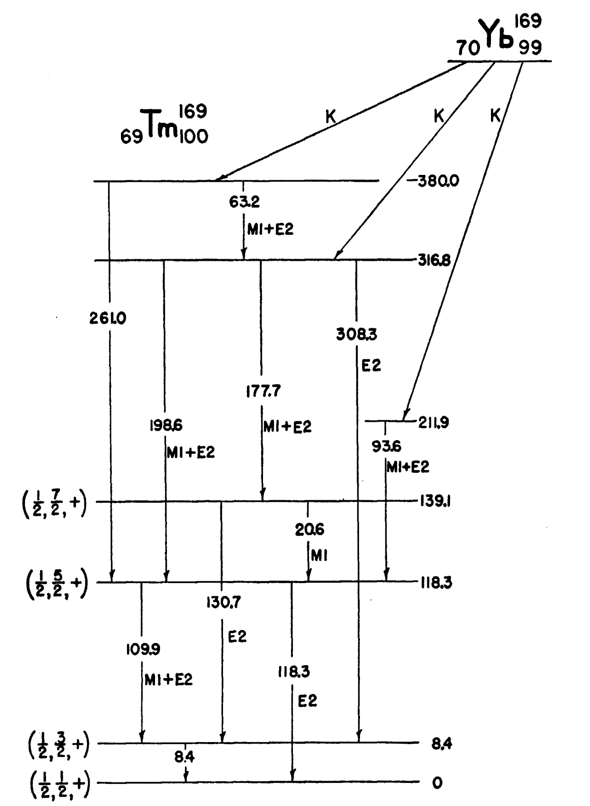

FIG. 2. Nuclear level scheme for Tm^{169} following K capture in Yb^{169}. (Energies in kev.) Spin along axis of symmetry, total spin, and parity are shown in parentheses.

of a equal to -0.74. From our values for the energies of the first three levels (8.4, 118.3, and 139.1 kev), a is obtained by comparing each of the upper energies with the lowest. Its value is found to be -0.775 and the excellent agreement between calculated and observed energies for the first three levels is shown in Table III. The lack of agreement for the two higher spins indicates that these possible rotational levels are not observed. Since the rotational levels are of the same parity, short-lived transitions between them can be only $M1$ or $E2$ in nature, in agreement with the multipolarity assignments noted in Table II.

From the results with the source in the crystal well, support is obtained for the arrangement of levels as shown in Fig. 2. A metastable level of half-life 6×10^{-7} second had been observed[2] in Tm^{169} and it was believed to be derived from K capture directly. It now appears

TABLE III. Energies in kev of rotational levels, together with observed energies.

I	Calculated	Observed
3/2	...	8.4
5/2	118.8	118.3
7/2	138.6	139.1
		316.8
9/2	337	
11/2	368	
		380.0

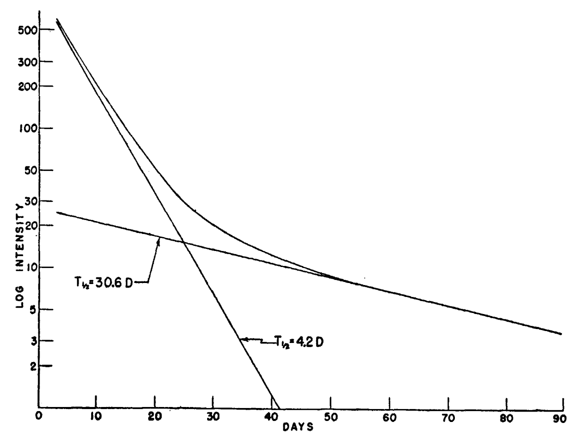

FIG. 3. Analysis of the decay curve for Yb.

from the summation evidence that the 316.8-kev level is most likely the delayed state. The presence of an unsummed x-ray peak strongly suggests a K-capture branch terminating at this level. The highest summation level appears to be 317 kev, which is reasonable since the transitions above it could not be included because of the delay. The increased peak height at 115 kev could be due to the sum of 63 kev and Tm x-rays (50 kev). The placement of the strongly converted 93-kev gamma transition is based on the augmented peak at 263 kev which could be the sum of 118, 93, and 50 kev.

The level at 211.9 kev is expected to be a single particle state, which may be either $d_{5/2}$ or $g_{7/2}$ in agreement with the shell model and the $M1$ character of the 93.6-kev transition. The 316.8-kev level should also be a single-particle level. It is observed that if this level is assigned a spin of 3/2 and the moment of inertia is assumed to be the same as in the ground state, the first rotational excitation will come 62.2 kev higher, as compared with the observed transition of 63.2 kev.

An analysis of the rate of decay shown in Fig. 3 indicates half-lives somewhat different than previously found.[1] This must be due to the higher purity of the Yb specimen. The long half-life of Yb^{169} appears to be 30.6 ± 0.2 days. The previously reported intermediate

TABLE IV. Conversion electron energies in kev in Lu^{175} following β emission from Yb^{175}.

Electron energy	Interpretation	Energy sum
50.5	K	113.8
74.5	K	137.8
81.7	K	145.0
103.1	L_1	114.0
103.6	L_2	114.0
104.9	L_3	114.1
111.7	M	114.2
113.5	N	114.0
127.3	L_1	138.2
219.6	K	282.9
272.6	L_2	283.0
333.5	K	396.8
386.5	L	397.4
394.9	M	397.4

half-life of 6.7 days attributed to Lu^{177} could not be observed. For Yb^{175} the half-life is 4.2±0.1 days. The absence or extreme weakness of the 6.7 day Lu^{177} activity as noted both in the decay curves and in the lack of conversion lines for the well known gamma transitions in Hf raises a serious question. The previous observation of the rather strong activity must have been due to Lu being present in the Yb as an impurity. Since Yb^{176} is abundant (12.7%) in all Yb, it is difficult to understand why Yb^{177} with its half-life of 1.88 hours would not build up the Lu^{177} daughter activity. Either the capture cross section in Yb^{176} is very small, which does not appear to be the case, or some assignment of mass may be in error.

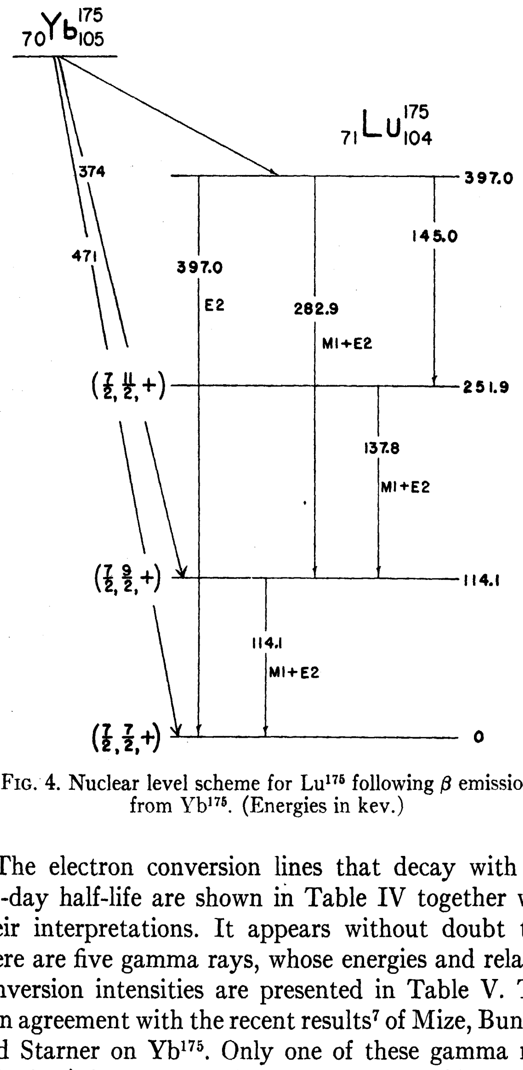

FIG. 4. Nuclear level scheme for Lu^{175} following β emission from Yb^{175}. (Energies in kev.)

The electron conversion lines that decay with the 4.2-day half-life are shown in Table IV together with their interpretations. It appears without doubt that there are five gamma rays, whose energies and relative conversion intensities are presented in Table V. This is in agreement with the recent results[7] of Mize, Bunker, and Starner on Yb^{175}. Only one of these gamma rays (114 kev) is observed[8] in the decay of Hf^{175}. In the Coulomb excitation of Lu^{175} both of the levels 114 and 252 kev are found to exist.[9] The K/L ratios for the 114- and 397-kev gammas were determined from microphotometer traces of the photographic plates. The

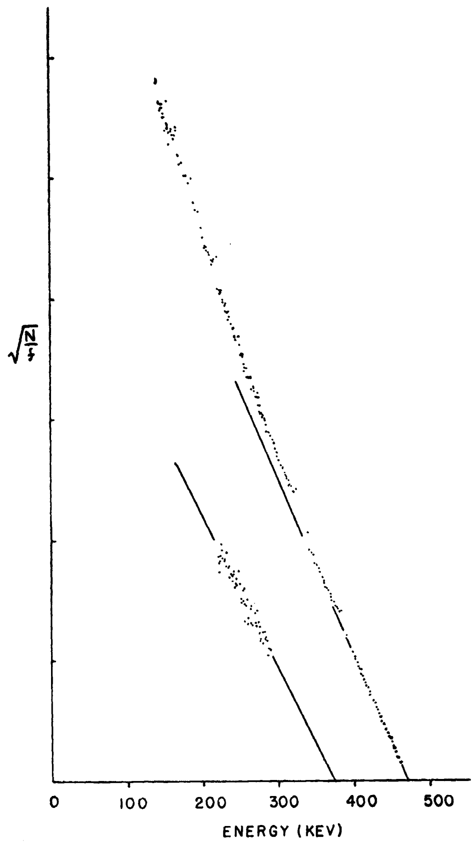

FIG. 5. Kurie plot of the β spectrum of Yb^{175}.

values for the 138- and 283-kev transitions are based upon visual estimates of the blackness of the lines. The choice of $M1$, $E2$ for the 114-kev gamma is based upon the agreement with calculations[4] for the L_1/L_2 ratio, and is supported by agreement with the empirically expected[10] K/L ratio. To satisfy the observed K/L ratio and the presence of a strong L_2 line for the 283-kev gamma a mixture of $E2$ and $M1$ transitions also appears likely. The other selections are based upon the K/L ratios together with the assumption of very short lifetimes. A nuclear level scheme for Lu^{175} based upon excellent energy fits is presented in Fig. 4.

The spin of the ground state in Lu^{175} has been measured to be 7/2, which from shell theory is interpreted as $g_{7/2}$. If the lower energy levels are regarded as ro-

TABLE V. Gamma energies in kev in Lu^{175} and relative electron line intensities. (The symbol x indicates that only one L line was observed.)

Gamma energy	K/L	L_1	L_2	L_3	Multipolarity
114.1	2.9±0.4	10	4.1	2.7	$M1, E2$
137.8	~2				$E2$
145.0					
282.9	~6		x		$M1, E2$
397.0	5.4±0.3				$E2$

[7] Mize, Bunker, and Starner, Phys. Rev. 99, 671 (1955).
[8] Burford, Perkins, and Haynes, Phys. Rev. 99, 3 (1955).
[9] G. Temmer and N. Heydenburg, Phys. Rev. 94, 1399 (1954).
[10] M. Goldhaber and A. Sunyar, Phys. Rev. 83, 906 (1951).

TABLE VI. Relative intensities of the K–L–L auger lines.

	K–L_I–L_I	K–L_I–L_{II}	K–L_I–L_{III}	K–L_{II}–L_{II}	K–L_{II}–L_{III}	K–L_{III}–L_{III}
Observed	1.0	1.6	1.5	...	2.0	0.9
Calculated[a]	1.0	1.02	1.65	0.24	1.46	0.81

[a] See reference 13.

tational in nature, then their energies may be calculated from that of the gamma ray of lowest energy. As the spins are given successive values of 9/2, 11/2, etc. and the 114-kev gamma regarded as basic, then the following levels should have energies of 253.6 and 418.5 kev. The 253-kev value is in good agreement with an experimental level, as shown in Fig. 4. The level at 397 kev is sufficiently divergent from the expected 418-kev value, to assume that it is not rotational. The transitions between the rotational levels, with no change in parity, should be $M1$ or $E2$ or a combination of both, agreeing with the choices indicated in Table V. The 397-kev level is expected to be a single-particle state. The multipolarities of the various gamma rays, together with the fact that the energy available in beta decay will permit at most an ordinary first forbidden transition, suggest that this level has spin 9/2 and even parity, with an $f_{7/2}$ ground state for Yb^{175}. The spin of 9/2 for the 397-kev level is in agreement with the angular correlation work of Akerlind *et al.*[11]

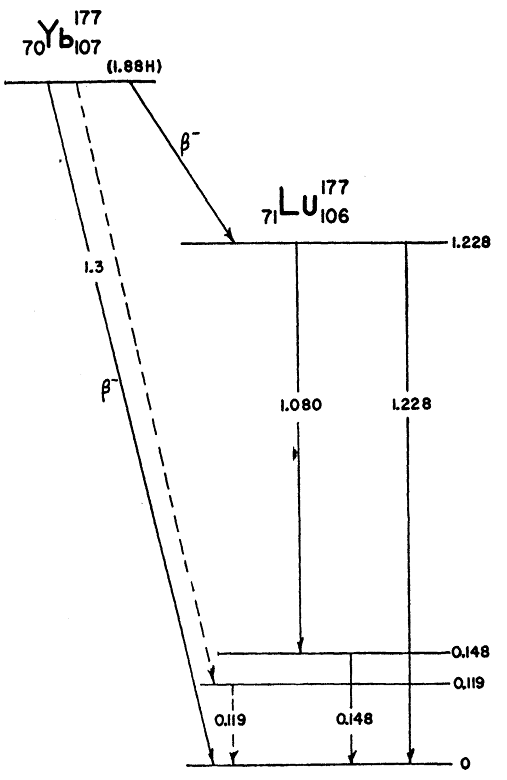

FIG. 6. Nuclear levels in Lu^{177} following β emission in Yb^{177}. (Energies in Mev.)

The beta spectrum of Yb^{175} was observed with the double-focusing magnetic spectrometer, using a Scotch tape source and Zapon ($\sim$15 micrograms per square centimeter) counter window, with a resolution of 0.5%. The Kurie plot is shown in Fig. 5. The spectrum appears to be complex, with an upper energy limit of 471 ± 3 kev. After subtraction of this high-energy component, there is found to be a rather large scatter in the points of the residual Kurie plot. A least squares fit to these points in regions where no interference from internal conversion lines is expected gives a component of maximum energy 374 ± 30 kev, whose intensity is about 25% that of the high-energy component. The level scheme requires an additional low-energy component at about 80 kev, which would be difficult to observe due to the many internal conversion lines in this region.

The activity in Yb^{177} was induced by short irradiation in the maximum flux region of the pile and was studied in a ten channel scintillation spectrometer and magnetic photographic spectrometer near the pile. A recent paper reports[12] the existence of two gamma rays of energy 119 and 146 kev and three beta rays with a maximum energy of 1.3 Mev. In the present investigation two additional high-energy gamma rays are found with energies of $1.228+0.005$ and 1.080 ± 0.005 Mev. The former is undoubtedly a cross-over transition for the 1.080- and 0.148-Mev gammas which are found to be in coincidence. All gamma rays appear to decay with a half-life of 1.88 ± 0.1 hr. The gamma ray reported at 119 kev has not been identified but is included as a dotted line in the provisional level scheme shown in Fig. 6. It has previously been assumed that the ground state of Lu^{177} has a half-life of 6.7 days followed by the emission of certain well-known highly converted gamma rays in Hf^{177}. It is quite certain that this activity, if present at all, is extremely weak in the high-purity Yb source.

Auger electrons following K-capture to Tm^{169} were also observed. Their relative intensities, determined from microphotometer traces of the photographic plates, are presented in Table VI, together with the calculated intensities of Hill[13] for $Z=80$.

[11] Akerlind, Hartmann, and Wiedling, Phil. Mag. 46, 448 (1955).
[12] H. deWaard Phil. Mag. 46, 445 (1955).
[13] R. D. Hill, Phys. Rev. 91, 770 (1953).

III

DECAY OF Ca^{49} AND Sc^{49}

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Decay of Ca^{49} and Sc^{49}†

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Ca^{49} has been found to decay with a half-life of 8.9±0.2 minutes. It emits two principal beta components of energies 2.12±0.10 and about 1.0 Mev in coincidence, respectively, with gamma rays of 3.07±0.05 and 4.04±0.06 Mev. The intensity ratio of these two branches is 8.5:1. The intensity of a possible ground-state beta branch is less than 1%, and that of a possible 0.98-Mev gamma transition between the 3.07- and 4.04-Mev levels is less than 3%. These data indicate that these excited states are respectively the single-particle $p_{\frac{3}{2}}$ and $f_{\frac{5}{2}}$ levels available for excitation of the twenty-first proton in Sc^{49}. Sc^{49} is found to emit in turn a single beta component of energy 1.80±0.10 Mev.

I. INTRODUCTION

UNTIL recently little was known of the decay of Ca^{49} except for a report[1] that it emitted beta rays of 2.7 Mev with a half-life of 8.5 min. The daughter Sc^{49} has been reported[2] to emit a single beta ray of 2.00 Mev with a half-life of 57 min. The decay of Ca^{49} seemed to be of particular interest from the point of view of the single-particle model since the daughter Sc^{49} nucleus has a closed shell of 28 neutrons and one proton outside the closed shell at 20. Beta-decay systematics[3] indicated that there should be about 5 Mev of energy available for the decay. It seemed possible that one might see in this case the relatively pure single-particle excited states available to the twenty-first proton and expected to lie 3 Mev or more above the ground state.

A very recent report[4] has verified that this is indeed the case. Two gamma rays of 3.10 and 4.05 Mev were observed with intensities in the ratio 9.0:1. This is consistent with the belief that the excited states from which they originate are the $p_{\frac{3}{2}}$ and $f_{\frac{5}{2}}$ levels respectively, while the ground state is $f_{7/2}$. One additional gamma ray was observed at 4.68 Mev with intensity indicating that 0.38% of the decays passed through the corresponding level. There was found to be no direct beta transition to the ground state. The highest energy beta component, leading to the 3.10-Mev excited state, was reported to be 1.95 Mev, giving a Q-value for the decay of 5.05 Mev. The half-life was reported to be 8.75 min. The daughter Sc^{49} was found to decay with a period of 57.2 min and emit a single beta ray of 2.05 Mev.[5]

† This work was carried out under the auspices of the U. S. Atomic Energy Commission.
* University of Michigan, Ann Arbor, Michigan.
[1] E. der Mateosian and M. Goldhaber, Phys. Rev. **79**, 192 (1950).
[2] L. Koester, Z. Naturforsch. **9a**, 104 (1954).
[3] K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).
[4] O'Kelley, Lazar, and Eichler, Phys. Rev. **102**, 223 (1956).
[5] *Note added in proof.*—See also M. McKeown and G. Scharff-Goldhaber, reported in *Nuclear Level Schemes A = 40–92*, edited by K. Way *et al.* (U. S. Atomic Energy Commission Report TID-5300, 1955). A gamma ray of 3.00 Mev is reported to be in coincidence with a beta ray of 2.0 Mev.

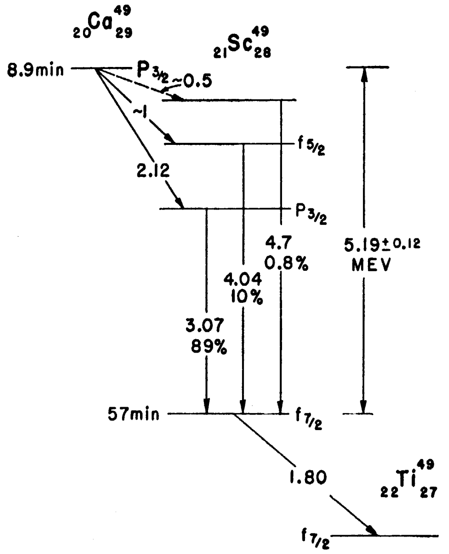

FIG. 1. Decay scheme of Ca^{49} and Sc^{49}.

Simultaneous independent studies at this Laboratory have led to results in essential agreement with the above, except for some discrepancy in the beta-ray energies. The improved results obtained since our preliminary report[6] are briefly summarized below.

II. EXPERIMENTAL RESULTS

The gamma-ray spectrum was studied using $2\frac{1}{4}$-inch cubic NaI(Tl) crystals and the Argonne 256-channel pulse-height analyzer. The spectrum observed in a well-collimated arrangement indicated only two gamma rays of energies 3.07±0.05 and 4.04±0.06 Mev and intensity ratio 8.5:1. The 4.68-Mev gamma ray reported by O'Kelley *et al.*,[3] was at first overlooked, but on closer examination the data are consistent with its existence. Our data indicate an energy 4.7±0.1 Mev and an intensity representing 0.8% of the decays. The entire pulse spectrum was found to decay with a half-life of 8.9±0.2 minutes, except for a low-energy continuum due to Sc bremsstrahlung. Calibration was based on the 4.45-Mev gamma ray of a Po—Be source, and on the gamma rays and sum peak of Na^{24}.

Pulse distributions taken in coincidence with each of the several peaks associated with these two gamma rays yielded no pulses above the random coincidence rate other than those due to annihilation quanta and back-scattered Compton quanta. In particular, the intensity of a possible 0.98-Mev gamma ray in cascade with the 3.07-Mev radiation does not have an intensity in excess of about 3% of the latter.

Beta-gamma coincidence absorption curves were obtained in which the beta rays were detected by an anthracene crystal. Beta rays of 2.12±0.10 Mev were found to be coincident with the 3.07-Mev gamma ray, and others of about 1.0 Mev were in coincidence with the 4.04-Mev gamma ray. The source was left undisturbed until the Ca activity had disappeared, after which the absorption curve of the beta rays of the Sc^{49} daughter was obtained. The result gave an energy of 1.80±0.10 Mev. The discrepancy between these results and those of O'Kelley *et al.*,[3] in the relative energies of the Sc and Ca beta rays is well outside quoted errors.

Anthracene pulse distributions of the beta rays were in qualitative agreement with the absorption results. From these distributions, the intensity of a possible 5.2-Mev ground-state beta branch can be asserted to be less than one percent. Logft values deduced from this fact and from the gamma-ray intensities indicate that all three transitions to the 3.07-, 4.04-, and 4.7-Mev levels are allowed, while the ground-state transition is at least 2nd forbidden. Also, the Sc beta transition is allowed. All these statements are fully consistent with the level assignments shown in Fig. 1. The assignments shown are just those predicted by the single-particle model, and are identical with those of O'Kelley *et al.*[3] The lack of a strong 0.98-Mev transition between the 4.04- and 3.07-Mev levels indicates that their assignments cannot be interchanged. Crude single-particle estimates[7] of transition probabilities predict that a 0.98-Mev $M1$ transition would be several times as probable as a 4.04-Mev $E2$ transition.

The Q-value of the decay obtained from our results is 5.19±0.12 Mev.

Thanks are expressed to Dr. O'Kelley, Dr. Lazar, and Dr. Eichler for communication of their results in advance of publication.

[6] Martin, Burson, and Cork, Phys. Rev. **100**, 1236(A) (1955).

[7] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

IV

RADIOACTIVE DECAY OF TERBIUM-161

Reprinted from the Bulletin of the American Physical Society, Series II, Vol. 1, No. 6, 297, June 21, 1956

Radioactive Decay of Terbium-161. J. M. CORK, M. K. BRICE, L. C. SCHMID, AND R. G. HELMER, *University of Michigan.*—A specimen of Gd^{160} enriched from its normal 21.9% up to 95.4% was irradiated in the heavy water pile for a week. The Gd^{161} formed by neutron capture decays by beta and gamma emission with a half-life of 3.7 min to radioactive Tb^{161}. Spectrometric studies of this activity show it to decay with a half-life of 7.15 days emitting both beta and gamma rays most of which have previously not been evaluated. The gamma rays are highly converted as evidenced by some forty electron conversion lines. Using the work functions for Dy there appear to be eight gamma rays whose energies are −25.6, 27.7, 48.9, 57.3, 74.8, 78.3, 106.2, and 132.1 kev. These energies fit remarkably well in a scheme with nuclear levels at 25.6, 74.8, 104.0, and 132.0 kev. Coincidence data with the scintillation spectrometer support the proposed plan. The beta spectrum appears to be composite with a maximum energy at 540 kev for which the log *ft* is about 6.6.

V

DECAY OF Mo^{101} (14.6 min)

Reprinted from the Bulletin of the American Physical Society,
Series II, Vol. 1, No. 7, 329, November 23, 1956

Decay of Mo^{101}(14.6 min).* D. W. MARTIN AND S. B. BURSON, *Argonne National Laboratory,* AND J. M. CORK, *University of Michigan.*—The radiations emitted in the decay of 14.6-min Mo^{101} have been studied with the Argonne 256-channel coincidence scintillation spectrometer and with magnetic spectrographs. Ten major gamma rays of 0.080, 0.191, 0.510, 0.590, 0.704, 0.890, 1.024, 1.18, 1.56, and 2.08 Mev can be resolved in the normal spectrum. In coincidence experiments, evidence is obtained for at least twelve additional weaker transitions of 0.193, 0.300, 0.40, 0.51, 0.70, 0.84, 0.95, 1.14, 1.28, 1.38, 1.46, and 1.66 Mev. At least six distinct beta components of about 2.2, 1.6, 1.2, 0.8, 0.7, and 0.6 Mev can be discerned in beta-gamma coincidence experiments. The beta component of highest energy is in coincidence with the 0.590-Mev gamma ray. The strong 0.191-Mev gamma transition is not in prompt coincidence with beta rays; the half-life of the upper state has been determined to be about 9.1×10^{-4} sec. The K-conversion coefficient of this transition is 0.30 ± 0.06. The probable character is therefore $M2$ or $E3$, with no possibility that it can be $M4$. A decay scheme is proposed that is compatible with all the many gamma-gamma and beta-gamma coincidences observed and with the estimated intensities of all components. The scheme involves eleven excited states of Tc^{101} at 0.191, 0.510, 0.590, 0.70, 0.84, 0.89, 1.21, 1.59, 1.98, 2.08, and 2.16 Mev. The ground state is probably $g_{9/2}$.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

VI

NUCLEAR LEVELS IN Dy^{161}

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Printed in U. S. A.

Nuclear Levels in Dy^{161}†

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University of Michigan, Ann Arbor, Michigan

(Received June 6, 1956)

A specimen of Gd^{160} enriched from its normal 21.9% up to 95.4% was irradiated in the Argonne heavy water pile. The Gd^{161} formed by neutron capture decays by beta and gamma emission with a half-life of 3.7 min to radioactive Tb^{161}. Spectrometric studies of this activity show it to decay with a half-life of 7.15 days emitting both beta and gamma rays many of which previously have not been evaluated. There appear to be seven gamma rays in Dy, all internally converted, whose energies are: 25.6, 27.7, 48.9, 57.3, 74.8, 78.3, and 106.2 kev. These energies fit into a scheme with nuclear levels at 25.6, 74.8, 103.9, and 132.0 kev. Coincidence data with the scintillation spectrometer support the proposed plan. The beta spectrum, studied with the double focusing spectrometer, appears to be complex, having three components whose energies are 531, 447, and 405 kev, with relative intensities of 68%, 22%, and 10%, and log *ft* of 6.7, 6.9, and 7.2, respectively.

GADOLINIUM-161 formed by neutron capture in Gd^{160} decays with a 3.7 minute half-life to terbium-161. This activity in turn emits beta and gamma radiation with a half-life found in the present investigation to be 7.15 days, terminating in dysprosium-161. A gamma transition of energy 49.0 kev had been reported[1] for this activity. An additional gamma ray of energy approximately 75 kev and a beta upper energy of 550 kev were observed[2] by the scintillation method. Coulomb excitation by alpha rays on unseparated dysprosium showed[3] gamma rays with energies of 76 and 166 kev, the latter probably not being in Dy^{161}. A proportional counter study of low-energy photons indicated a 26-kev transition.[4]

With the stronger sources now available a reinvestigation of the activity seemed desirable. A specimen of separated Gd^{160}, enriched up to 95.4 percent, was irradiated for a week in the maximum flux of the heavy water Argonne reactor. Beta energies were studied with the double focusing magnetic spectrometer, using a scotch tape backed source and 15 $\mu g/cm^2$ Zapon window. Gamma energies were evaluated from conversion electrons in magnetic spectrometers and coincidences observed with the scintillation spectrometer.

Some twenty-five electron conversion lines were observed and their energies measured as shown in column 1, Table I. The interpretation of these lines yields seven gamma energies, four of which had not been previously reported. The relative intensities of many of the lines were measured with the microphotometer and the relative values for each group shown in column 4. The clearly resolved 18.6-kev electron line was interpreted as an L_1 line for a gamma ray of 27.7 kev. Had this been a K line then an L_1 at 63.3 kev should have been expected, but it was not observed. In addition to the group of electron lines tabulated, all of which decayed with a half-life of 7.15 days, certain other lines persisted with a longer half-life. These were recognized as due to gamma rays in europium, which must have been present as an impurity, even in the separated terbium.

The relative intensities of the three L lines of the 25.6 kev and the 48.9-kev gamma rays are shown in Table II. These are compared with the calculated L shell coefficients of Rose *et al.*[5] for a pure $M1$ transition at this energy and for a sufficient admixture of $E2$ to be in agreement with the observed data. The possibility that the 25.6-kev gamma is an electric dipole transition is not completely excluded. The L_2 line of the 57.3

TABLE I. Conversion electron energies in Dy^{161} and their interpretation. (Numbers italicized in column 4 indicate arbitrary normalization for each group of lines.)

Electron energy, kev	Assignment	Energy sum, kev	Relative intensity	Gamma energy, kev
16.4	L_1	25.5	*10.0*	
17.0	L_2	25.6	7.5	
17.8	L_3	25.6	6.3	
23.6	M	25.6		
25.3	N	25.7		25.6
18.6	L_1	27.7		27.7
39.9	L_1	49.0	*10.0*	
40.3	L_2	48.9	1.6	
41.0	L_3	48.8	0.7	
46.9	M	48.9		
48.6	N	49.0		48.9
48.1	L_1	57.2	*10.0*	
48.6	L_2	57.2		
49.4	L_3	57.2	2.5	
55.6	M	57.6		
57.1	N	57.5		57.3
20.8	K	74.6	*10.0*	
65.8	L_1	74.9	5.5	
66.9	L_3	74.7	2.2	
73.0	M	75.0		
74.5	N	74.9		74.8
24.4	K	78.2		
69.2	L_1	78.3		78.0
52.4	K	106.2		
97.3	L_1	106.4		106.2

† This work was supported jointly by the Office of Naval Research and the U. S. Atomic Energy Commission.
[1] Cork, LeBlanc, Nester, and Stumpf, Phys. Rev. **88**, 685 (1952).
[2] R. Barloutaud and R. Bellini, Compt. rend. **241**, 389 (1955).
[3] N. Heydenberg and G. Temmer, Phys. Rev. **100**, 150 (1955).
[4] Scharff-Goldhaber, der Mateosian, McKeown, and Sunyar, Phys. Rev. **78**, 325(A) (1950).
[5] Rose, Goertzel, and Swift (unpublished).

TABLE II. Theoretical and observed relative L-shell intensities for the 25.6- and 48.9-kev gamma rays.

25.6-kev gamma	$\alpha_{L1}:\alpha_{L2}:\alpha_{L3}$	48.9-kev gamma	$\alpha_{L1}:\alpha_{L2}:\alpha_{L3}$
Pure $M1$	10:0.9:0.16	Pure $M1$	10:0.8:0.2
$M1+E2$(2%)	10:6.0:8.5	$M1+E2$($\frac{1}{2}$%)	10:1.1:0.6
Observed	10:7.5:6.3	Observed	10:1.6:0.7

gamma falls together with the N line of the 48.9-kev gamma ray so that its intensity and hence the multipolarity of the transition cannot be expressed with certainty, although the possibility of electric quadrupole is eliminated. The K/L ratio for the 74.8-kev gamma is compatible with an $E2$ transition. The multipolarities of the other weaker gamma rays were not determined.

A nuclear level scheme as shown in Fig. 1 satisfies both the observed energies and the relative intensities of the gamma rays. In this plan the 25.6-kev gamma ray should be the strongest. Actually its L lines photographically appear weaker than the L lines for the 48.9-kev gamma, but when the proper correction for the variation of emulsion sensitivity with energy is made, the expected relationship appears reasonable. To check the proposed level scheme coincidence measurements were made with a scintillation spectrometer. The fine resolution obtainable with the magnetic spectrometers could of course not be obtained with the scintillation device. The singles gamma-ray spectrum is found to consist of three broad peaks at 25, 50, and 76 kev, each of which is believed to be composite. Coincidences were observed between (76, 50); (50, 25); and (50, 50) kev gammas. When lead shielding is used so as to minimize the effect of backscattered iodine x-rays (28 kev), there still appeared to be a (25, 25) kev coincidence. These data are in accord with the arrangement shown.

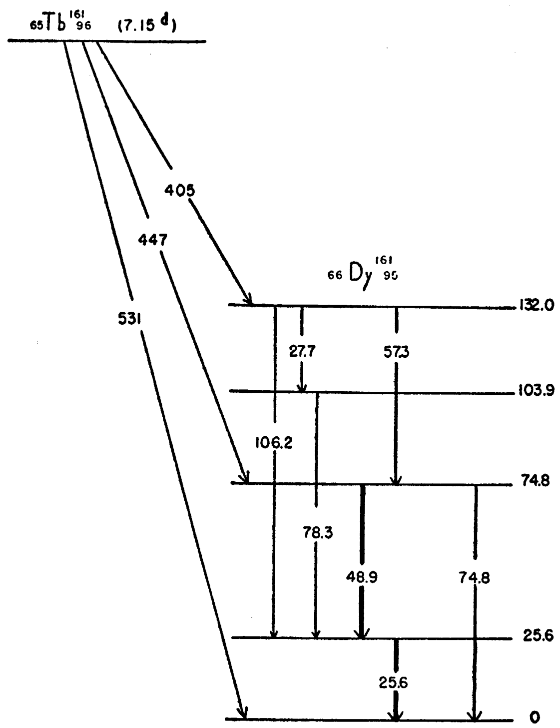

FIG. 1. Proposed nuclear energy level scheme for Dy^{161}. The heavy lines indicate the strongest transitions.

The Kurie plot of the beta spectrum was found to be complex. Since all gamma rays observed were of low energy, it was expected that the maximum energies of all beta components would lie rather close together. In order to avoid the large uncertainties resulting from

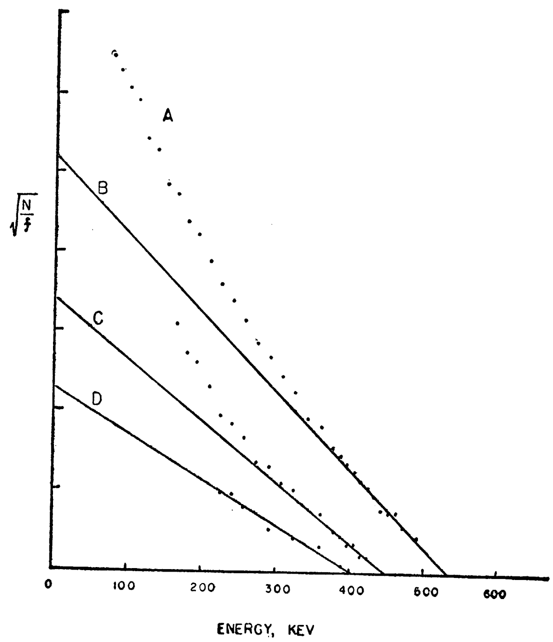

FIG. 2. Analysis of the Kurie plot of the beta spectrum of Tb^{161}. The set of points A represents the composite spectrum. The lines B, C, and D indicate the separate Kurie plots of the three components whose energies are 531, 447, and 405 kev. The points adjacent to C and D indicate the result of previous subtractions.

determining each component by only a few points near its upper limit, the set of experimental points was fitted as the sum of a number of components, assumed to be of allowed form, an assumption subsequently justified by the $\log ft$ values. It was found that two components were not sufficient but the data above 200 kev could be fitted well by three components, as shown in Table III and Fig. 2. Deviations below 200 kev are probably due, at least in part, to backscattering in the source.

The spin of the ground level in Dy^{161} has been observed and reported to be probably 7/2 in one report[6] and 5/2 in the other.[7] Odd parity is predicted by the shell model. Similarly the ground level in Tb^{161} is predicted to have even parity but the spin may have values 3/2, 5/2, or 7/2. This isotope lies in a region where rotational bands are to be expected. However, the levels at 25.6 and 74.8 kev cannot be the first two excited levels of a rotational band with a ground state spin

[6] K. Murakawa and T. Kamei, Phys. Rev. **92**, 325 (1953).

[7] A. H. Cooke and J. G. Park, Proc. Phys. Soc. (London) **A435**, 282 (1956).

greater than $\frac{1}{2}$. If the ground state spin is assumed to be $\frac{1}{2}$, then these two excited levels can be used to calculate a decoupling parameter $a=-0.071$, and the next rotational level is predicted at 134.5 kev. The vibration-rotation interaction correction, which is proportional to $I^2(I+1)^2$, for this 7/2 level amounts to about -2 kev, bringing the energy of the expected level into good agreement with the one observed at 132 kev. This apparent sequence of rotational levels seems to be fortuitous, however, since it is not supported by the observed ground state spin, Coulomb excitation studies,[3] or character of the beta transitions.

TABLE III. The resolution of the beta spectrum of Tb^{161}.

Maximum energy, kev	Percent abundance	Log ft	ΔI, parity
531±10	68%	6.7	0 or 1, yes
447±10	22%	6.9	0 or 1, yes
405±10	10%	7.2	0 or 1, yes

VII

DECAY SCHEME OF Pt^{199}

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Decay Scheme of Pt^{199}†

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(Received September 12, 1956)

The radiations of the 30-min activity of Pt^{199} have been investigated with 180° magnetic photographic spectrometers and a 10-channel coincidence scintillation spectrometer. This activity of platinum has been found to decay by the emission of four beta rays with maximum energies of 0.8, 1.1, 1.3, and 1.7 Mev. Gamma rays with energies of 0.074, 0.197, 0.246, 0.318, 0.475, 0.54, 0.71, 0.79, and 0.96 Mev were detected. Extensive beta-gamma and gamma-gamma coincidence measurements were made; and an energy level scheme is proposed which is consistent with the results of all of the experiments.

A THIRTY-MINUTE activity which is produced by neutron capture in platinum was first reported in 1935.[1,2] McMillan *et al.*[3] assigned this activity to Pt^{199}. In 1941, Krishman and Nahum[4] studied the radiations emitted in the decay of Pt^{199} and established, by means of aluminum absorption experiments, that beta rays with a maximum energy of 1.8 Mev are emitted.

Sources of Pt^{199} were obtained in the present investigation by neutron irradiation of normal PtO. Seven internal conversion electron lines were detected with 180° spectrographs and are listed in Table I. The interpretation of these lines are listed in column 2 of Table I, and the gamma-ray energies are listed in columns 3, 4, and 5. The lines at 124, 144, 155, and 190 kev are identified by their energies as internal conversion electron lines in Hg, due to gamma rays emitted in the decay of Au^{199}, the daughter product of Pt^{199}. The 268- and 332-kev electron lines have the $K-L$ energy difference of Pt and are assigned to the 80-min activity of Pt^{197m} which has been reported[5] to decay by the emission of a 337-kev gamma ray. The energy of this transition as determined in the present study is 346 kev. The remaining three electron lines are interpreted as K internal conversion electron lines of gamma rays emitted in the decay of Pt^{199}.

Table I. Energies and interpretations of the observed internal conversion electron lines.

Electron line energy in kev	Interpretation	Gamma-ray energies Pt	Au	Hg
116	Au K		197	
124	Hg K			208
144	Hg L			159
155	Hg M			159
165	Au K		246	
190	Hg L			208
235	Au K		316	
268	Pt K	346		
332	Pt L	346		

The photon spectra of the 30-min platinum activity was studied with a 10-channel coincidence scintillation spectrometer.[6]

The NaI(Tl) pulse-height distribution from the gamma-rays of a PtO source which was irradiated for about 15 minutes is shown as the top curve in Fig. 1. Because of the short irradiation times, the activities of Au^{199} and Pt^{197} were not observed in these sources. The various peaks in the distribution are interpreted as indicating the presence of nine gamma rays with energies of 0.074, 0.197, 0.246, 0.318, 0.475, 0.540, 0.715, 0.790, and 0.96 Mev. All of these peaks were observed to decay with a half-life of 30±3 min and are, therefore, assigned to Pt^{199}.

The peak at about 70 kev in the pulse-height distribution occurs at an energy rather close to that of the K x-rays of gold (67 kev). One might conclude that it is due entirely to the gold x-rays. The energy of the peak is, however, slightly higher than the x-ray energy. In order to determine if this is an energy shift due to the presence of a gamma ray of about this energy, the scintillation spectrometer was set so that the ten channels just covered this peak. Then, without changing the spectrometer, the pulse-height distributions due to Tl x-rays (71 kev), the Pt^{199} peak, and the Pt^{199} peak in coincidence with the 246-kev gamma rays, were re-

Table II. Gamma-gamma coincidences observed in Pt^{199}. Where coincidences were observed between two gamma rays, an X is placed at the intersection of the corresponding row and column. The symbol 0 is used for gamma rays which are not in coincidence and blank spaces indicate cases where no data are available.

Gamma rays (energies in kev) \ Gamma rays (energies in kev)	960	790	715	530	475	318	246	197	74
74		0	X	0	X	0	X	X	
197				X	X	X	X		X
246				0	X	0	0	X	X
318		0	0	0	X	0	0	X	0
475		0	0	0	0	X	X	X	X
530		0	0	0	0	0	0	X	0
715				0	0	0			X
790				0	0	0			0
960									

† Work performed under the auspices of the U. S. Atomic Energy Commission.
* University of Michigan, Ann Arbor, Michigan.
[1] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segrè, Proc. Roy. Soc. (London) A149, 522 (1935).
[2] McLennan, Grimmett, and Read, Nature 135, 147 (1935).
[3] McMillan, Kamen, and Ruben, Phys. Rev. 52, 375 (1937).
[4] R. S. Krishman and E. A. Nahum, Proc. Cambridge Phil. Soc. 37, 422 (1941).
[5] N. Hole, Arkiv Mat. Astron. Fysik 36A, No. 9 (1948).
[6] S. B. Burson and W. C. Jordan, Phys. Rev. 91, 498 (1953).

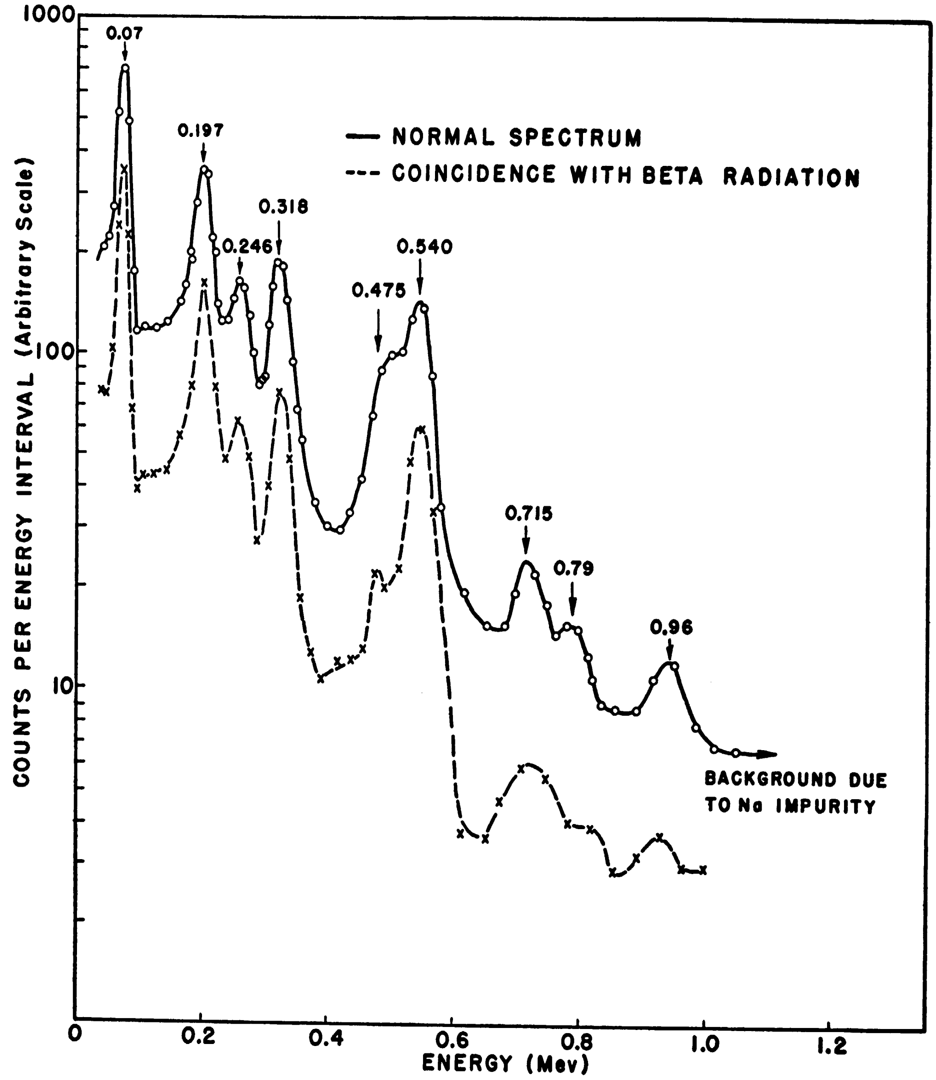

FIG. 1. The NaI pulse-height distribution of the gamma rays of $_{78}Pt^{199}$ (30 min).

corded. The results are illustrated in Fig. 2. It can be seen that the Pt^{199} peak in the normal distribution occurs at almost exactly the same energy as the Tl x-ray. This energy is 3 kev too high for the peak to be due entirely to Au x-rays. The fact that the Pt^{199} 70-kev peak is complex is clearly illustrated by the coincidence distribution (the dashed curve). The structure of this peak indicates the presence of a gamma ray at 74 kev. In addition, the small hump on the low-energy side of this peak occurs at about the energy of the Au x-ray. Thus, one concludes that a 74-kev gamma ray is emitted in the decay of Pt^{199}, and that the 70-kev peak in the normal distribution is a combination of this gamma ray and Au x-rays.

The pulse-height distribution of the gamma rays which are in coincidence with beta rays was measured and is shown as the dashed curve in Fig. 1. The 0.48, 0.71, 0.79, and 0.96 Mev gamma rays are not so strongly in coincidence with the beta rays as the other gamma rays. One explanation of this would be that these four gamma rays are transitions from a level which has a half-life which is comparable to the resolving time of the coincidence circuit, i.e., about 2 μsec.

By using an anthracene crystal for a beta-ray detector and measuring the attenuation in Al of the beta rays which are in coincidence with the various gamma rays, it was established that the 0.197- and 0.54-Mev gamma rays follow a beta ray which has a maximum energy of 1.1 ± 0.1 Mev. Similarly, it was established that the 0.246- and 0.318-Mev gamma rays follow a 1.3 ± 0.1-Mev beta ray, and the 0.71-, 0.79-, and 0.96-Mev gamma rays follow an 0.8 ± 0.1-Mev beta ray. A beta ray with a maximum energy of about 1.7 ± 0.2-Mev was detected in the singles aluminum absorption experiment, but was not observed to be in coincidence with any gamma rays. It is interpreted as a beta transition to the ground state of Au^{199}.

Extensive gamma-gamma coincidence measurements were made, and the results are summarized in Table II. The gamma rays are listed in the first row and column. Where coincidences are observed between two gamma rays, an X is placed at the intersection of the appro-

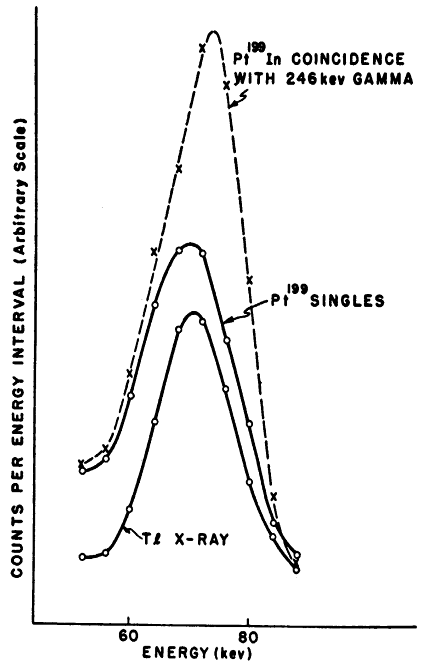

FIG. 2. NaI pulse-height distributions of the 70-kev peak.

priate row and column. Gamma rays which are not in coincidence are indicated by an 0, and the spaces are blank where no data are available.

Strong coincidences were observed between the 74-kev transition and several other gamma rays. The NaI pulse-height distribution of the gamma rays which are in coincidence with the 74-kev transition is shown as the dashed curve in Fig. 3. From this distribution, one can conclude that the 74-kev transition is in coincidence with 197-, 246-, 475-, and 715-kev gamma rays, and not in coincidence with the 318-, 540-, and 790-kev gamma rays. The small coincidence peaks at 318- and 540-kev are interpreted as due to coincidences with the x-rays resulting from the internal conversion of the

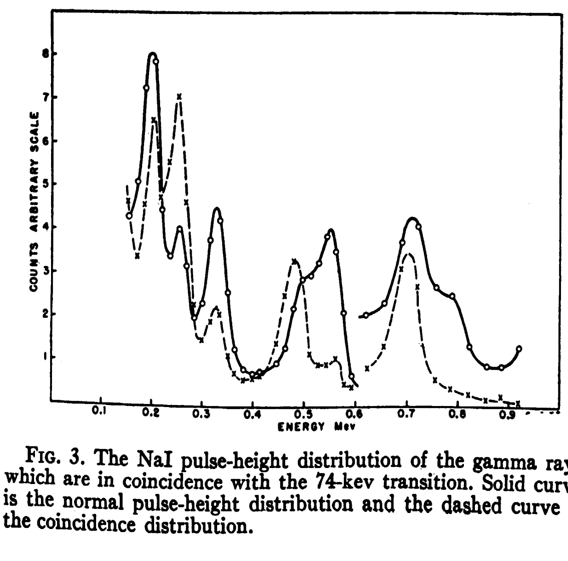

FIG. 3. The NaI pulse-height distribution of the gamma rays which are in coincidence with the 74-kev transition. Solid curve is the normal pulse-height distribution and the dashed curve is the coincidence distribution.

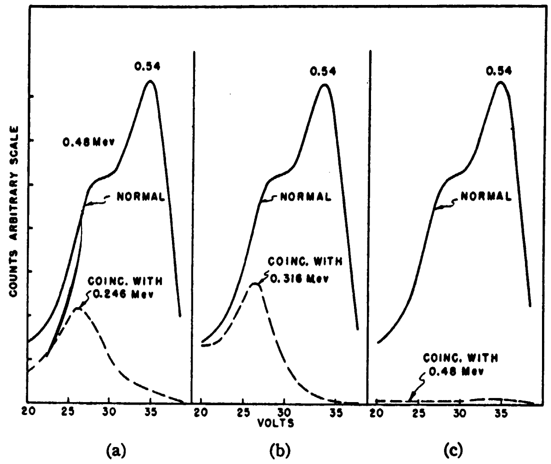

FIG. 4. Gamma-gamma coincidences in the 0.48- to 0.54-Mev region.

197-kev gamma ray. One striking feature of the coincidence distribution is the intensity of the 246-kev peak relative to the intensity of the 197-kev peak. If one assumes that a small portion of the 246-kev coincidence peak is due to coincidences with x-rays, then one can conclude that the 74-kev transition is in coincidence with approximately equal amounts of the 197-kev and the 246-kev gamma rays. Since the 197-kev photopeak in the normal distribution is considerably stronger than the 246-kev photopeak, the 197-kev transition must be in coincidence with more than just the 74-kev and the 246-kev transitions.

If one examines the pulse-height distribution of gamma rays which are in coincidence with the 197-kev photopeak, one finds that it is in coincidence with the

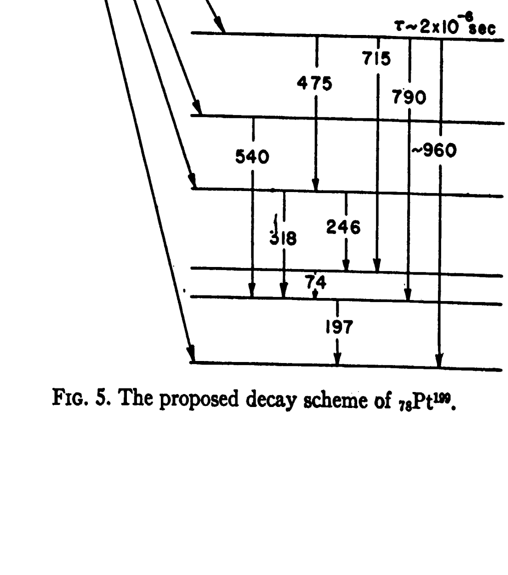

FIG. 5. The proposed decay scheme of $_{78}Pt^{199}$.

246-, 318-, 475-, and 540-kev transitions. The counting rates were not high enough to determine if the gamma rays with energies above 700 kev are also in coincidence with this transition.

The 0.48–0.54 Mev region of the pulse-height distribution is shown in Fig. 4. The normal pulse-height distribution is plotted in each part of the figure as a solid curve, and the distributions from gamma rays which are in coincidence with the 246-, 318-, and 475-kev photopeaks are plotted as dashed curves in (a), (b), and (c), respectively. From these curves one can conclude that the 475-kev gamma ray is in coincidence with both the 246- and 318-kev transitions, and that the 540-kev gamma ray is not in coincidence with the 246-, 318- or the 475-kev transitions. In a similar manner, it was established that the 246- and 318-kev radiations are not in coincidence with one another.

The proposed decay scheme for Pt^{199} is shown in Fig. 5. This scheme includes all of the beta rays and gamma rays which were detected in this study. The arrangement of the transitions is consistent with all of the coincidence measurements.