The Radiations of $_{64}Gd^{159}$(18 hr) and $_{64}Gd^{161}$(3.7 min)

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The radiations from $_{64}Gd^{159}$(18 hr) and $_{64}Gd^{161}$(3.7 min) are studied with 180° photographic electron spectrometers and a scintillation coincidence spectrometer.

$_{64}Gd^{159}$(18 hr): Internal conversion lines corresponding to gamma transitions of 57.5±0.3 and 364±3 kev are observed. Peaks due to the *K* x-ray and the 364-kev gamma ray are observed in the NaI pulse-height distribution. The results of coincidence measurements indicate that the two gamma transitions are not in cascade, but that the 57-kev one is preceded by a beta transition of ~1.1 Mev, while the 364-kev one is preceded by a beta transition of ~0.9 Mev.

$_{64}Gd^{161}$(3.7 min): The half-life of this activity is found to be 3.73±0.10 min. Aluminum absorption measurements indicate an energy of ~1.6 Mev for the beta transition. Peaks are observed in the pulse-height distribution corresponding to 44±1 (Tb *K* x-ray), 102±3, ~165, and ~360 kev. The high-energy peak is resolved into two peaks in coincidence distributions, showing the 360-kev transition to be coincident with the x-ray, and a 316-kev transition to be coincident with the 102-kev gamma ray. The *K* internal conversion line for the 316-kev transition is observed, plus some other weak conversion lines corresponding to the other transitions. All of the electromagnetic radiation appears to be coincident with a beta transition of ~1.6 Mev. The existence of a gamma transition of ~60 kev is suggested.

INTRODUCTION

In 1938 Pool and Quill[1] produced 18-hr and 3.5-min activities by means of both fast and slow neutrons on gadolinium. Both activities were tentatively assigned to mass number 159. Subsequent investigations[2–4] have indicated that the 18-hr activity does belong to mass 159, but that the short activity is associated with mass 161. Absorption measurements[2,3,5] have shown that the 18-hr activity decays by emission of a beta ray of about 0.9 Mev and electromagnetic radiations of approximately 0.055 and 0.35 Mev.

Reported values for the half-life of the short activity have varied from 3.3 to 4.5 minutes.[5–7] Absorption measurements[3,7] have indicated that a beta transition of about 1.5 Mev, a gamma ray of 0.37 Mev, and internal conversion electrons of approximately 0.066 Mev are associated with this activity. Church[8] has recently investigated both of these activities with a scintillation spectrometer. He has detected a 0.360-Mev gamma ray in the 18-hr activity and gamma rays of 0.110 and 0.320 Mev in the short activity.

In the present investigation, the radiations associated with these activities are studied with photographic electron spectrometers as previously described,[9] and a scintillation coincidence spectrometer. The scintillation coincidence spectrometer[10] is equipped with a ten-channel pulse-height analyzer on one side and a single-channel analyzer on the other. Either side can be operated independently as a single spectrometer. In coincidence studies, the output pulse from the single-channel side triggers the recording pulse in the ten-channel side. The coincidence resolving time is about 2 microseconds. NaI(Tl) and anthracene crystals are used as scintillators for gamma and beta radiations, respectively. Some of the preliminary scintillation spectrometer data were obtained with a twenty-channel spectrometer kindly made available by B. Hamermesh. We are grateful for the use of this instrument.

Sources of gadolinium oxide were irradiated in the Argonne heavy-water-moderated reactor. The gadolinium oxide was supplied by Research Chemicals Incorporated, Burbank, California and was specified to be 99.9 percent pure. Upon activation it was found that a trace of europium was present. (The 9.3-hr Eu^{152} activity was easily detected by means of *K*, *L*, and *M* conversion lines associated with the 122-kev transition. Also, peaks indicating this, as well as other higher energy europium gamma rays, were observed in the pulse-height distribution.)

RESULTS

$_{64}Gd^{159}$(18 hr): A sample of the gadolinium oxide was irradiated for approximately 55 hours in the reactor to produce sources for the conversion electron study. Initial spectrograms revealed the presence of many electron groups. Some of these are associated with activities of longer life than the 18-hr activity, and some with a 9.3-hr europium contaminant. By a series of exposures it was found that six lines were attributable to the 18-hr activity. These may be interpreted as arising from internally converted gamma rays of

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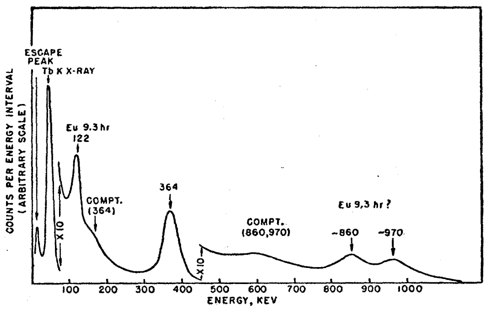

FIG. 1. Gamma ray pulse-height distribution resulting from $_{64}Gd^{159}$(18 hr). Peaks due to europium contamination are also present.

57.5 ± 0.3 and 364 ± 3 kev, using the electron binding energies of terbium (see Table I).

Although K conversion of the 57.5-kev gamma ray is energetically possible, the electrons would have an energy below the minimum detectable by the spectrometer. Visual estimates of the line intensities indicate that L conversion occurs mostly in the L_1 sub-shell, which suggests an $M1$ transition.[11] The K and L electron lines of the 364-kev transition are weak. The K/L ratio appears to be large, but it is not determined with sufficient accuracy to identify the character of the radiation.

The pulse-height distribution obtained from a sample of gadolinium oxide several hours after irradiation is shown in Fig. 1. The peaks corresponding to the 364-kev gamma ray and the Tb K x-ray (as well as its associated escape peak) were observed to decay with the 18-hr period. The other peaks decayed with a half-life of about 10 hours. By comparison with peaks resulting from a europium source, these were shown to be due to europium contamination. There is a small contribution to the x-ray peak due to a 49-kev transition following the beta decay of Tb^{161}(6.8 day), which is the daughter of Gd^{161}(3.7 min). The unconverted portion of the 57.5-kev transition is apparently small relative to the intense 44-kev Tb K x-ray and is unresolved.

Coincidence experiments failed to reveal any (x-ray)–(364-kev gamma) coincidences, indicating that the 57.5 and 364-kev transitions are not in cascade. Although some of the pulses contributing to the 44-kev peak were in coincidence with others of about the same energy, these coincidences are attributable to the K capture activity of either the europium contaminant or that of 236-day Gd^{153}.

Coincidences between beta rays and the 364-kev gamma ray and between beta rays and x-rays were observed. The (beta)–(gamma) coincidence rate is attenuated by aluminium absorbers on the beta side with a half-value thickness of about 29 mg/cm^2, while the (beta)–(x-ray) coincidence rate is attenuated with a half-value thickness of about 43 mg/cm^2. These absorption values indicate the presence of two beta components whose energies are approximately 0.9 and 1.1 Mev. The (beta)–(x-ray) coincidence rate was observed to decay with the 18-hr half-life, and the slope of the absorption curve was the same on two successive days after the initial experiment. Hence, these coincidences may be assigned to the 18-hr activity.

TABLE I. Internal conversion electrons associated with $_{64}Gd^{159}$(18 hr).

Electron energy (kev)	Proposed interpretation	Energy sum (kev)	Transition energy (kev)	Estimate of intensity ratios
48.8	L_1(Tb)	57.5	57.5 ± 0.3	$L_1/L_3 \gg 1$
50.0	L_3(Tb)	57.5		
55.5	M_1(Tb)	57.5		
56.9	N(Tb)	57.3		
312	K(Tb)	364	$364\ \pm3$	K/L large $\gtrsim 5$
~353	L(Tb)	~362		

From these data it may be concluded that two beta-ray branches exist, each followed by a single gamma ray. It seems reasonable to propose the nuclear energy level scheme as shown in Fig. 2.

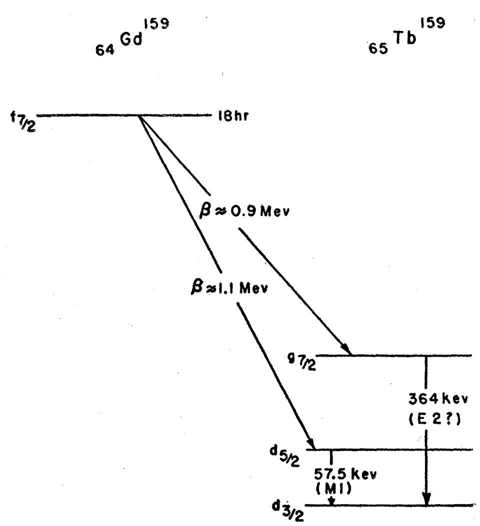

FIG. 2. Proposed decay scheme for $_{64}Gd^{159}$(18 hr).

The spin of the ground state of Tb^{159} has been measured[12] and found to be 3/2. Shell theory predicts the ground state of Gd^{159} to be $f_{7/2}$, while $g_{7/2}$ and $d_{5/2}$ are possible assignments for low lying states of Tb^{159}. If one postulates an equal branching ratio for the two beta transitions, the log ft values would be about 6.8 and 7.3, indicating both would be first forbidden with spin change 0 or 1. A $d_{5/2}$ assignment to the 57.5-kev level is consistent if the transition is magnetic dipole ($M1$). A $g_{7/2}$ assignment to the 364-kev level is also consistent if this transition is electric quadrupole ($E2$).

$_{64}Gd^{161}$(3.7 min): Measurements of the half-life of the short-lived gadolinium activity yield an average

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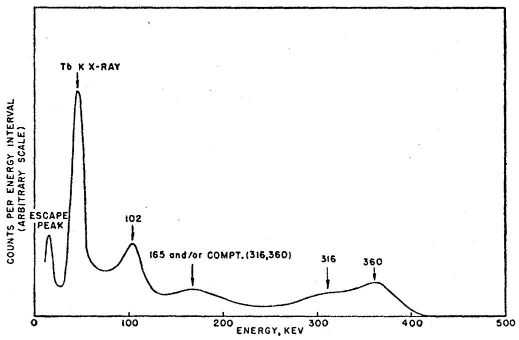

FIG. 3. Gamma ray pulse-height distribution resulting from $_{64}Gd^{161}$(3.7 min).

value of 3.73±0.10 min. Aluminum absorption of the beta radiation indicates a maximum energy of approximately 1.6 Mev. Internal conversion electron lines associated with this activity are not strong. A line at 264 kev may be interpreted as due to *K* conversion of a 316-kev gamma ray. Other weak lines, possibly associated with this activity, are observed at 47.4, 53.4, ~305, ~310, and ~350 kev. In one attempt to build up the intensity of the weak lines, three hundred successive irradiations and exposures were made on a single spectrogram.

The pulse-height distribution obtained with the scintillation spectrometer is shown in Fig. 3. There are peaks corresponding to energies of 44±1 (Tb *K* x-ray), 102±3, ~165, and ~360 kev. All of these were observed to decay with the 3.7-min period. The "360"-kev peak is broad and distorted in comparison with other single gamma-ray peaks of approximately this energy. The appearance suggests the presence of another gamma ray of about 320 kev, which may be interpreted as the 316-kev transition, previously mentioned. These two peaks are well resolved in coincidence pulse-height distributions as shown in Fig. 4. The 316- and 102-kev gamma rays are in coincidence, while the 360-kev gamma ray is coincident with the *K* x-ray. A shoulder at 316 kev appears in the coincidence distribution corresponding to the latter combination. This may be attributed to coincidences between the 316-kev gamma ray and *K* x-rays resulting from conversion of the 102-kev gamma ray. The coincidence rates in each case were observed to decay with the 3.7-min period.

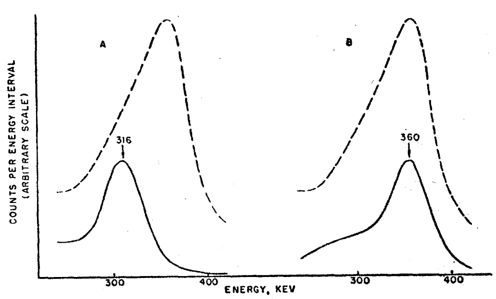

FIG. 4. Gamma coincidence pulse-height distributions resulting from $_{64}Gd^{161}$(3.7 min). A. Coincidence distribution in region of "360"-kev peak with the single-channel spectrometer set at the 102-kev peak; B. Corresponding distribution with single-channel spectrometer set at the x-ray peak. For comparison, the normal distribution is shown with a dashed curve in both figures. Only the position of the peaks is to be compared, since the scales are not the same.

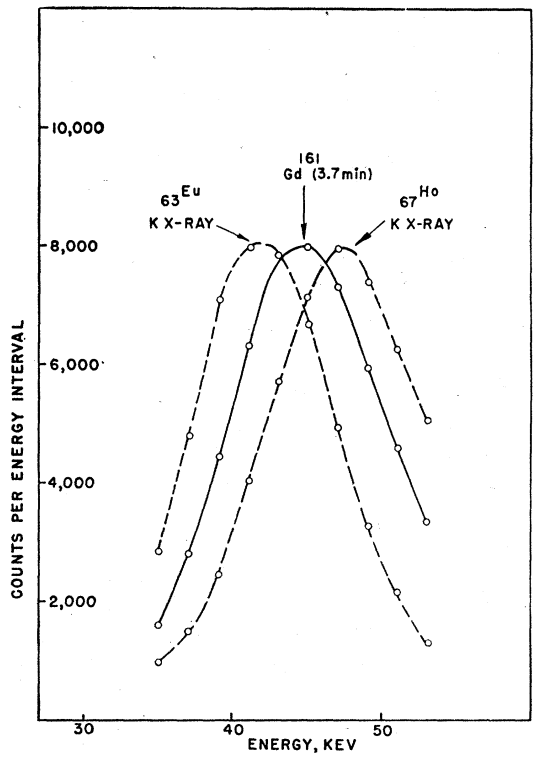

FIG. 5. Pulse-height distribution in the region of the *K* x-ray. The solid curve is the distribution resulting from $_{64}Gd^{161}$(3.7 min). The dashed curves are distributions resulting from *K* x-rays of europium ($Z=63$) and holmium ($Z=67$).

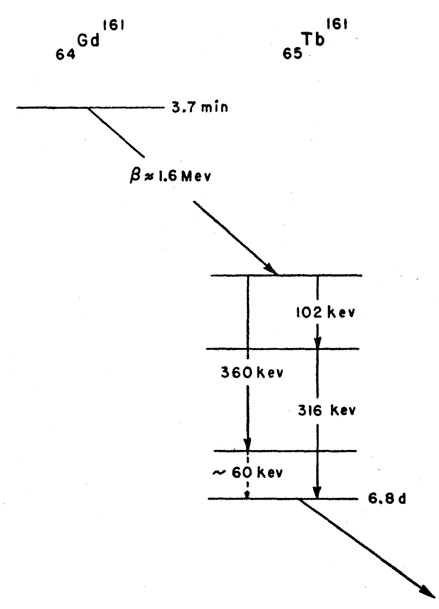

FIG. 6. Proposed decay scheme for $_{64}Gd^{161}$(3.7 min).

No coincidences between the 316- and 360-kev gamma rays were observed. Except for the possible existence of a metastable state, this precludes the possibility of these two transitions being in cascade.

The results of (gamma)–(gamma) coincidence experiments involving the 165-kev peak are inconclusive. A peak in the coincidence pulse-height distribution is observed in this region when the single-channel spectrometer is set at 150–200 kev. These coincidences are probably due to Compton scattering of the higher energy gamma rays in the detecting crystals.

Because the coincidences between the K x-ray and the 360-kev gamma ray are easily observed (the ratio of coincidence counting rate to single counting rate being approximately the geometry factor), and since conversion lines are not easily observed, the possible presence of a K capture activity was suspected. K capture in gadolinium would result in the emission of x-rays characteristic of europium; x-rays associated with internal conversion following beta decay would be characteristic of terbium. The energy resolution of the spectrometer is not good enough to permit a reliable Z assignment to the x-ray. However, by comparing the pulse-height distribution with those due to x-rays of europium and holmium (Fig. 5), it is evident that the x-ray peak is not due to europium and is probably characteristic of terbium. As an additional check, the attenuation of the peak due to absorbers of La, Ce, Pr, and Nd was observed. The relative attenuation effected by each of these absorbers was approximately the same. This also indicates that the x-ray is not the Eu x-ray, since if it were, its energy would lie between the critical edges of Ce and Pr, and a striking difference in absorption should be noted. Additional evidence indicating that no K capture activity is present was obtained from (beta)–(gamma) and (beta)–(x-ray) coincidence experiments. The results of such experiments indicate that all of the electromagnetic radiation is coincident with a beta ray of approximately 1.6 Mev.

The foregoing data may be explained by postulating the existence of a highly K converted transition of about 60 kev which is in cascade with the 360-kev transition in Tb. A careful inspection of the pulse-height distribution in the region of 60 kev failed to reveal any evidence of an unconverted gamma ray of this energy. Electrons resulting from K conversion of such a transition would have an energy below the detection limit of the conversion electron spectrometers, hence would not be observed on the photographic plates. The weak 47.4- and 53.4-kev internal conversion lines may be due to L and M conversion electrons for this transition. However, one or the other of these might also be attributed to K conversion of the ~102-kev gamma ray.

The 165-kev peak in the pulse-height distribution may be interpreted either as resulting from a gamma ray of this energy or as the Compton distribution due to the 316- and 360-kev radiations. Although the former interpretation is preferred from a consideration of the line shape, the decay scheme (Fig. 6) which is proposed is consistent with all of the remaining data without inclusion of the possible 165-kev transition.

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Gamma-Gamma Directional Correlation Experiments with Mo^{93m}†

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Three directional correlations have been measured involving the three successive γ rays emitted following the 7.0 hour state in Mo^{93m}. The data characterize the spins and multipoles as

$$J+8 \xrightarrow{2^4} J+4 \xrightarrow{2^2} J+2 \xrightarrow{2^2} J,$$

which is consistent with Goldhaber's postulation on the basis of "core isomerism."

THE 7.0-hour isomer of Mo has now been assigned[1–3] to Mo^{93m} and three γ rays of 0.264, 0.685, and 1.479 Mev are known[1–5] to be emitted in cascade following the decay of the isomeric state. It has been pointed out by Goldhaber[6] that the main features of the decay scheme suggest a phenomenon of "core isomerism," where the odd neutron (presumably in a $g_{7/2}$ state) couples to the even-even core which successively goes through states with spins 8+, 4+, 2+, 0+ to give a total spin to the four states involved of 23/2+, 15/2+, 11/2+, and 7/2+. As one means of establishing the spins of the four levels experimentally, directional correlation measurements

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