PHYSICAL REVIEW C VOLUME 3, NUMBER 1 JANUARY 1971

Experimental Studies of Neutron-Deficient Gadolinium Isotopes. III. The Strange Case of Gd^{145g}

R. E. Eppley and Wm. C. McHarris

Department of Chemistry and Cyclotron Laboratory,† Department of Physics, Michigan State University, East Lansing, Michigan 48823*

and

W. H. Kelly

Cyclotron Laboratory,† Department of Physics, Michigan State University, East Lansing, Michigan 48823

(Received 20 August 1970)

The γ rays emitted following the decay of 21.8-min Gd^{145g} have been studied using Ge(Li) and NaI(Tl) detectors in a variety of singles, anticoincidence, pair-coincidence, and two-dimensional ("megachannel") coincidence experiments. Of the 38 γ rays attributed to this decay, 27 (accounting for >97% of the intensity) have been placed in a consistent decay scheme that includes 20 states in Eu^{145}. All of the single-proton states between $Z=50$ and 82 are seen (including the $h_{11/2}$ state populated directly by the decay of Gd^{145m}), and the associated β and γ transitions are accounted for quite well using simple shell-model arguments. In addition, we propose an explanation for the abrupt change in decay properties of the $N=81$ isotones that occurs at Gd^{145g}, viz., the lack of observable population directly to the Eu^{145} ground state but 72.6% of its decay going to states at 1757.8 and 1880.6 keV. With a $(\nu s_{1/2})^{-1}$ ground state for Gd^{145}, these "fast" β transitions can be represented as

$$(\pi h_{11/2})^{2n}(\nu s_{1/2})^{-1} \rightarrow (\pi h_{11/2})^{2n-1}(\nu h_{9/2})(\nu s_{1/2})^{-1},$$

making the final states another example of three-quasiparticle states being populated by the β^+/ϵ decay of nuclei below $N=82$.

I. INTRODUCTION

This investigation continues our over-all studies of the neutron-deficient Gd isotopes, the decay[1] of Gd^{149} and the characterization[2] of the isomer, Gd^{145m}, having been reported previously.

Although several earlier papers speculated on Gd^{145}, Grover[3] in 1959 seems to have been the first to characterize this nuclide to any degree of clarity. It was also reported at about the same time by Olkowsky *et al.*[4] Both sets of results, having been obtained with NaI(Tl) detectors, were incomplete. A good example is the fact that the two intense γ-ray transitions at 1757.8 and 1880.6 keV were unresolved. The NaI(Tl) data showed these as a composite peak reported to have an energy of 1.75 MeV,[3] although with some insight Grover decided that there were two transitions, but he did not elucidate further.

As far as we have been able to determine, no conversion-electron studies have ever been made on Gd^{145g} decay, and, indeed its short half-life (21.8 min; cf. Sec. III D below) and the high energies of its stronger transitions make such experiments impracticable. And until the recent paper by Newman *et al.*,[5] no high-resolution [i.e., Ge(Li)] γ-ray studies had been reported. The lack, now and in the foreseeable future, of electron data cripples one in trying to assemble a complete decay scheme, for he has to work without direct information on the multipolarities of the transitions. However, the spins and parities of a number of the lower-lying states in the daughter Eu^{145} were determined by Newman *et al.*[5] through an analysis of the $Sm^{144}(\tau,d)Eu^{145}$ reaction. This reaction tends to discriminate against complex states, and, as will be seen later in this paper, we have reason to believe that the primary states populated by the decay of Gd^{145g} are complex. Our work has proceeded in parallel with the work of Newman *et al.*, and there has been exchange of information between the groups.[6] They concentrated on the (τ, d) studies, however, taking only singles γ-ray spectra, whereas we have concentrated on γ-ray studies, using various coincidence and anticoincidence techniques. Their experiments thus excite and explain many of the more straightforward lower-lying states that we see only weakly or not at all. On the other hand, we see evidence of a number of higher-lying states populated or depopulated by weak γ rays, and we think that we can explain what we call the "strange case" of Gd^{145g} decaying overwhelmingly to the two states at 1757.8 and 1880.6 keV in Eu^{145}. Here, then, is an excellent case where β-γ spectroscopy from one laboratory and reactions spectroscopy from another laboratory supplement and complement each other.

By the "strange case" we mean the abrupt break in the decay properties of the odd-mass $N=81$ isomer pairs[2] that occurs at Gd^{145g}. By now there is a well-known series of seven $N=81$ isomer pairs, the ground state in each case presumably being a single $d_{3/2}$ neutron hole in the $N=82$ closed shell, and the metastable state being a single $h_{11/2}$ neutron hole in the same shell. The metastable states decay exclusively to the ground states via an $M4$ transition in the lighter-mass isotones, although recently some direct branching has been observed from Sm^{143m} decay[7] and Gd^{145m} decay[2] to the $h_{11/2}$ states in Pm^{143} and Eu^{145}. More germane to the present work, on the neutron-deficient side of the series the $(\nu d_{3/2})^{-1}$ ground states of $_{58}Ce^{139}$, $_{60}Nd^{141}$, and $_{62}Sm^{143}$ (Geiger *et al.*,[8] Beery, Kelly, and McHarris,[9] and DeFreene,[10] respectively) all decay in a very straightforward fashion to the $\pi d_{5/2}$ states in their daughter nuclei. *A priori* there was no reason to expect the decay of $_{64}Gd^{145g}$ to behave otherwise, yet it was soon discovered there there is essentially no decay to the $\pi d_{5/2}$ ground state of Eu^{145} – its unhindered decay populates the two aforementioned high-lying states. We now think we have a reasonable explanation for this, involving: (1) a crossing of the $\nu d_{3/2}$ and $\nu s_{1/2}$ orbits such that the ground state of Gd^{145} is really $(\nu s_{1/2})^{-1}$, coupled with (2) a shift downward in energy of the $\pi h_{11/2}$ orbits, allowing an appreciable $(\pi h_{11/2})^{2n}$ component in the Gd^{145} wave function. There is now indirect evidence[2,5] for both of these, and if they be true, the decay of Gd^{145} can be described as a "straightforward decay" into high-lying three-quasiparticle states, somewhat analogous to the decay[11] of Nd^{139m}. This will be discussed in some detail below.

II. SOURCE PREPARATION

Gd^{145g} sources were prepared primarily by the $Sm^{144}(\tau, 2n)Gd^{145}$ reaction, which has a Q value of -10.6 MeV.[12] Beams of τ particles at 20 MeV (the threshold for Gd^{144} production), furnished by the Michigan State University (MSU) sector-focused cyclotron, were used to bombard enriched targets of $Sm^{144}{}_2O_3$ (95.10% Sm^{144}, obtained from the Isotopes Division, Oak Ridge National Laboratory). Typically, 25-mg targets were bombarded for 1–2 min with 0.5 μA of beam current. We also used the $Sm^{144}(\alpha, 3n)Gd^{145}$ reaction ($Q=-30.9$ MeV) to prepare a few sources, bombarding similar targets with 40-MeV α particles from the MSU cyclotron.

It is interesting to note the competing reactions that can accompany (τ, xn) reactions. After a bombardment at MSU to produce Gd^{143} by the $Sm^{144}(\tau, 4n)Gd^{143}$ reaction ($Q=-31.2$ MeV) using 40-MeV τ's, we found that we had produced quite a pure source[13] of Sm^{141m+g}, most likely by a $Sm^{144}(\tau, \alpha 2n)Sm^{141}$ reaction ($Q=-9.8$ MeV). Also, on attempting to produce Dy^{147} by the $Nd^{142}(C^{12}, 7n)Dy^{147}$ reaction ($Q=-74.9$ MeV) using 70–120-MeV C^{12} beams from the Yale University heavy-ion accelerator, we found a sizable amount of Gd^{145} to be present, presumably through the competing $Nd^{142}(C^{12}, \alpha 5n)Gd^{145}$ reaction ($Q=-56.2$ MeV). And, as a climax we found we were also able to produce Gd^{145} by the $Sm^{144}(C^{12}, 2\alpha 3n)Gd^{145}$ reaction ($Q=-38.4$ MeV), which has an unexpectedly large cross section. It must proceed by a combination of cluster stripping and compound-nucleus formation. The low binding energies of α particles in these neutron-deficient nuclei below $N=82$ and the fact that α particles can efficiently carry away large amounts of angular momentum make for large cross sections for evaporating α particles as well as neutrons. Not only does this cause a large number of different nuclides to be made in most bombardments, thus complicating the task of analysis, but also it may set a practical limit on the use of standard bombarding techniques for the production of nuclei farther from stability in this region.

Our bombardments with the 20-MeV τ beam did, however, produce quite pure sources of Gd^{145g}. Here, apparently, the bombarding energy was too low for any competing $(\tau, \alpha xn)$ reactions. The next higher-mass nuclide, Gd^{146}, which should still have an appreciably formation cross section at this energy has a half-life of 48 days and thus posed no problem. In addition, Eu^{145} has a half-life of 5.9 days and a well-worked-out decay scheme,[14] so we did not have to worry about contamination of the spectra by daughter transitions.

Each source was counted within 2–3 min of the end of the bombardment and counted for varying intervals of time up to a maximum of 80 min, approximately four half-lives. The γ rays attributed to Gd^{145} decay all retained their constant relative intensities over this period.

III. EXPERIMENTAL DATA

A. Singles γ-Ray Spectra

Two separate Ge(Li) detectors were used to obtain the Gd^{145g} γ-ray spectra. One has a 7-cm^3-active-volume five-sided coaxial detector [≈0.5% efficient for the Co^{60} 1333-keV γ ray, compared with a 3×3-in. NaI(Tl) detector at 25 cm] manufactured in this laboratory, the other a 2.6% efficient detector manufactured by Nuclear Diodes, Inc. The best resolution we obtained was 2.3 keV full width at half maximum for the Co^{60} 1333-keV peak. Both detectors were used with room-temperature field-effect transistor preamplifiers, linear amplifiers having near-Gaussian pulse shaping and pole-zero compensation, and 4096-channel analyzers or analog-to-digital convertors (ADC) interfaced to computers.

The γ-ray energies were determined by counting the spectra simultaneously with the standards listed in Table I of Ref. 1. The larger peaks in the spectrum were first calibrated by use of the standards. These calibrated peaks, in turn, were used to determine the energies of the weaker peaks in spectra taken without the standards. The centroids and net peak areas were determined with the aid of the computer code SAMPO.[15] The backgrounds were first subtracted and the centroids then determined by fitting the peaks to Gaussian functions having exponential tails on both the upper and lower sides of the peaks. The specific peak shapes were determined by comparisons with reference peaks specified at intervals throughout the spectrum. The energies were then determined by fitting the centroids to a quadratic calibration equation. Peak areas were then converted to γ-ray intensities through curves previously determined in this laboratory[16] for each detector. These curves were obtained by using a set of standard γ-ray sources whose relative intensities had been carefully measured with a 3×3-in. NaI(Tl) detector.

A word about the energies of the higher-energy γ rays ($E_\gamma > 1880.6$ keV): Because of the weakness of these peaks it was not possible to observe them in spectra when standards were counted simultaneously. Thus, we had to resort to an extrapolation of our calibration curves up into this region. Various polynomial extrapolations were tried and discarded, for we found that a linear extrapolation gave the best agreement between the energies of the photopeak and those determined from double-escape peaks falling within our well-calibrated energy range. One should be somewhat wary, however, of systematic errors in the energies of these γ rays.

After taking spectra from and following the decay of at least 15 different Gd^{145g} sources prepared at widely differing times, we have identified 38 γ rays as resulting from the β^+/ϵ decay of Gd^{145g}. A singles spectrum taken with the 7-cm^3

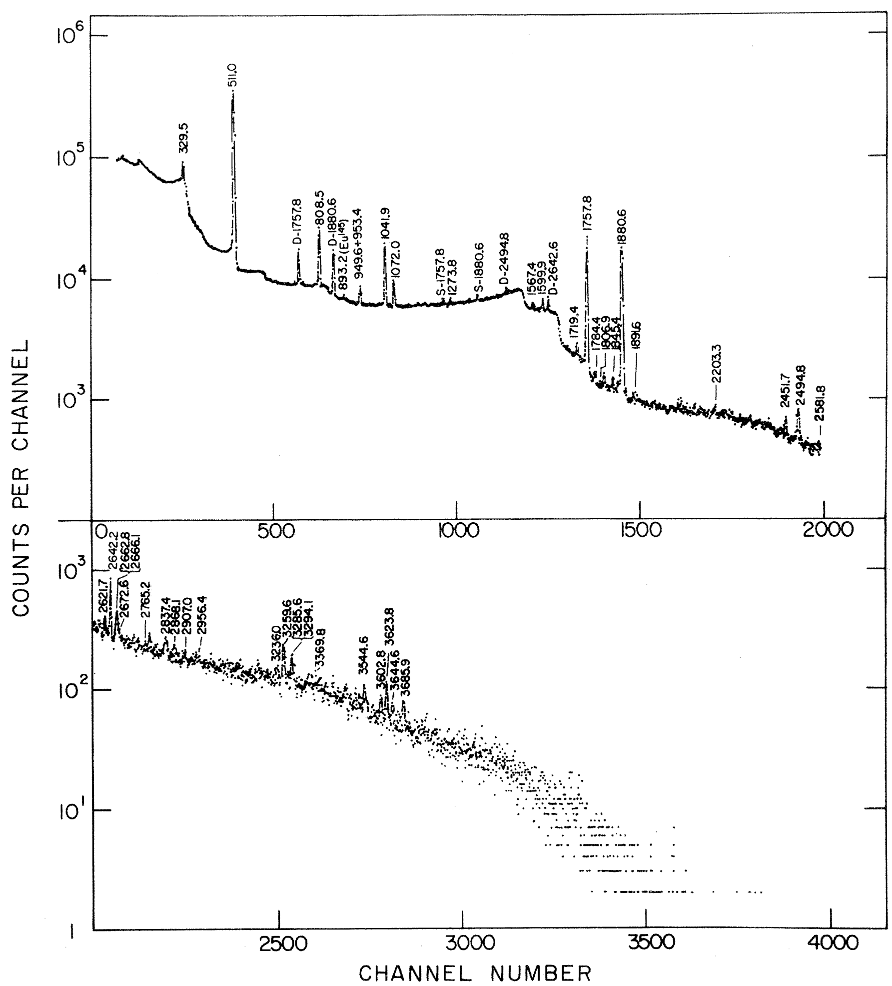


FIG. 1. Gd^{145g} singles γ-ray spectrum taken with a 7-cm^3 Ge(Li) detector.

detector is shown in Fig. 1. A list of these γ rays and their relative intensities is given in Table I, where they are compared with the results of Newman *et al.*[5] All values from our work are the averages from many determinations, with the quoted errors reflecting the statistical fluctuations found among the different runs and the quoted errors on the standards used.

B. Coincidence Spectra

1. Anticoincidence spectra. One of the most convenient "first steps" in elucidating a complex decay scheme such as that of Gd^{145g} is to determine which transitions are ground-state transitions, especially primarily ϵ-fed ground-state transitions. To obtain such information we performed an anticoincidence experiment between the 7-cm^3 Ge(Li) detector and an 8×8-in. NaI(Tl) split annulus. This setup has been described in detail elsewhere,[17] but in brief it works as follows: The Ge(Li) detector is placed inside one end of the annulus tunnel and a 3×3-in. NaI(Tl) detector is used to plug the other end. The Ge(Li) detector is operated in an anticoincidence mode (resolving time, $2\tau \approx 200$ nsec) with either (optically isolated) half of the annulus or the 3×3-in. detector. Thus, the system serves both as a Compton-suppression and, more important, as a cascade-suppression spectrometer. An anticoincidence spectrum is shown in Fig. 2, and the relative intensities of the γ rays in this spectrum are compared with those in the singles spectra in Table II.

2. Megachannel coincidence spectra. Our two-dimensional "megachannel" coincidence experiment utilized two Ge(Li) detectors, the Nuclear Diodes 2.5% detector and an ORTEC 3.6% detector. A block diagram of the electronics is shown in Fig. 3. The experiment was much like a standard fast-slow coincidence experiment, except that both the x and y events were processed each time a fast-coincident event was detected. The x and y addresses were stored in the two halves of a single (32-bit) word in a dedicated buffer in the MSU Cyclotron Laboratory Sigma-7 computer. When the buffer was filled, events were collected in a second, similar buffer while the contents of the first were written on magnetic tape. The spectra were recovered later off-line by a program that allowed one to obtain gated "slices" with or without a linearly interpolated background subtraction.[18]

The short half-life of Gd^{145g}, coupled with the fact that there just are not too many coincidences associated with its decay, makes it difficult to obtain "pretty" coincidence spectra. In order to record as many coincidence events as possible during a limited counting time, we used a 180° geome-

TABLE I. Energies and relative intensities of γ rays from the decay of Gd^{145g}

This work		Ref. 5	
Energy (keV)	Intensity [a]	Energy (keV)	Intensity [b]
329.5 ± 0.2	30.8 ± 2.0	330.1	31
808.5 ± 0.2	≡100	808.4	≡100
949.6 ± 0.3	8.6 ± 0.3	949.4	5.9
953.4 ± 0.3	15.8 ± 0.3	953.7	11.8
1041.9 ± 0.2	112 ± 4.0	1041.9	107
1072.0 ± 0.4	31 ± 1.0	1072.2	17.6
1567.4 ± 0.2	10.4 ± 0.2	1567.5	10.2
1599.9 ± 0.2	20 ± 0.4	1599.9	19.6
1719.4 ± 0.2	13.3 ± 0.1	1719.5	11.8
1757.8 ± 0.3	380 ± 10	1757.9	392
1784.4 ± 0.4	4.8 ± 0.2		
1806.9 ± 1.0 [c]	2.7 ± 0.3		
1845.4 ± 0.4	6.3 ± 0.1	1844.7	4.7
1880.6 ± 0.5	364 ± 10	1880.6	384
1891.6 ± 0.3	4.9 ± 0.2		
2203.3 ± 0.2	2.2 ± 0.1	2202.8	7.1
2451.7 ± 0.5	3.6 ± 0.2		
2494.8 ± 0.5	14.5 ± 0.5	2494.3	15.3
2581.8 ± 0.4	3.0 ± 0.2		
2642.2 ± 0.5	21.6 ± 0.2	2642.9	25.9
2662.8 ± 0.4 [c]	6.7 ± 0.7	2663.2	3.5
2666.1 ± 0.4 [c]	7.2 ± 0.1		
2672.6 ± 0.9	1.8 ± 0.2	2674.0	2.4
2765.2 ± 1.5	1.9 ± 0.1		
2837.4 ± 0.3	4.6 ± 0.4	2837.7	9.8
2868.1 ± 0.7	1.3 ± 0.1		
2907.0 ± 0.4	1.2 ± 0.1		
2956.4 ± 0.2 [c]	1.5 [d]		
3236.0 ± 0.5	1.6 ± 0.2		
3259.6 ± 0.6	2.2 ± 0.2		
3285.6 ± 0.5	1.7 ± 0.1		
3294.1 ± 0.5 [c]	1.4 [d]		
3369.8 ± 0.5 [c]	0.8 [d]		
3544.6 ± 0.5 [c]	1.6 [d]		
3602.8 ± 0.5 [c]	1.0 [d]		
3623.8 ± 0.5 [c]	2.1 [d]		
3644.6 ± 0.5 [c]	0.9 [d]		
3685.9 ± 1.6 [c]	1.4 [d]		
		781.3 [e]	3.1
		914.6 [e]	2.7
		1070.2 [e]	9.8
		1781.9 [e]	7.1

[a] The errors given on the intensities reflect only the statistical scatter about the average over many runs. The absolute uncertainties will be larger, perhaps ±10% for the more intense peaks and correspondingly greater for the less intense peaks.

[b] The intensities given in Ref. 5 were renormalized so that the 808.4-keV $\gamma \equiv 100$.

[c] These γ rays show up only weakly (but consistently) in the spectra, so we place them only ***tentatively*** as originating from Gd^{145g} decay.

[d] These intensities may well be off by as much as a factor of 2.

[e] Transitions reported in Ref. 5 for which we found no corresponding transitions. See the text for a discussion of these transitions.

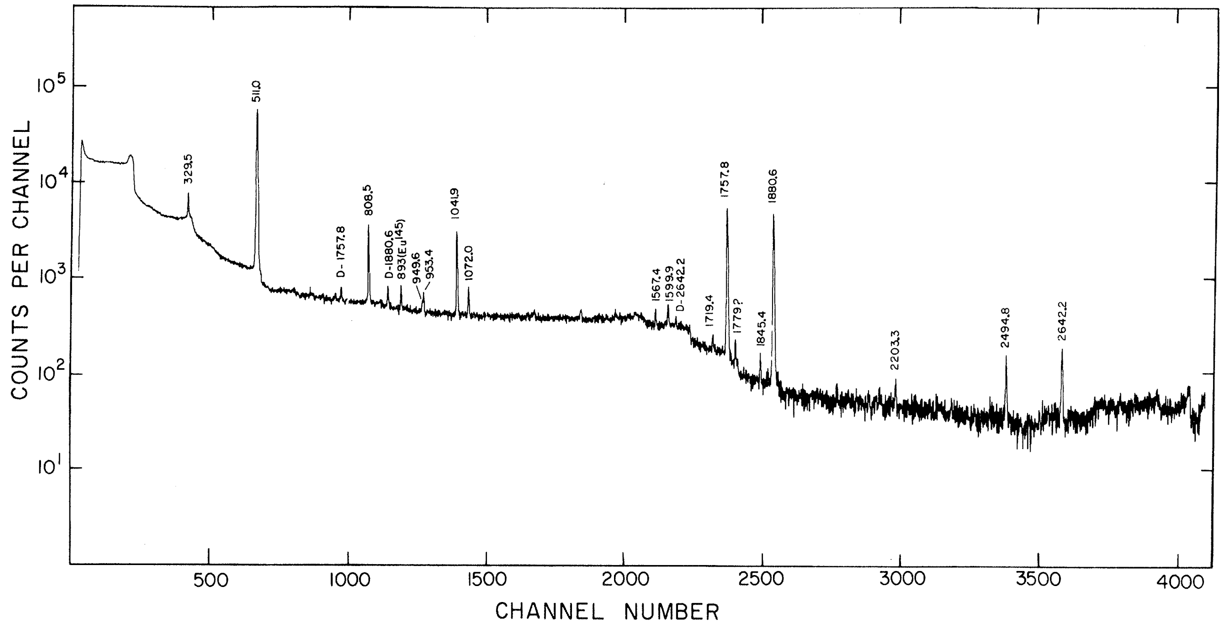


FIG. 2. Gd^{145g} anticoincidence γ-ray spectrum. This spectrum was recorded with a 7-cm^3 Ge(Li) detector placed in one end and operated in anticoincidence with an 8×8-in. NaI(Tl) split annulus. An additional 3×3-in. NaI(Tl) detector, also operated in anticoincidence with the Ge(Li) detector, blocked the other end of the tunnel.

try for the detectors, although this can cause serious complications because of Compton scattering between the detectors.[19] With repeated bombardments during a 1-day period we were able to collect 1.8×10^6 coincidence events, which were then analyzed. The integral coincidence spectra for the x (2.5%) and y (3.6%) detectors are shown at the top of Fig. 4(a), and six gated spectra (gates on x, display from y), including background subtraction, are shown in the remainder of Fig. 4(a)

TABLE II. Relative intensities of Gd^{145g} γ rays in coincidence experiments.

	Relative intensities			
Energy[a] (keV)	Singles	Integral coincidence	511-511-γ-ray coincidence	Anti-coincidence
329.5	30.8	60		24
808.5	≡100	≡100	≡100	86
949.6	8.6	18.4		5.5
953.4	15.8	19.3		11
1041.9	112	85.6	28.0	112
1072.0	31	35.6		21
1567.4	10.4			11
1599.9	20		0.64	21
1719.4	13.3	13.5		6.6
1757.8	380	214	100	507
1784.4	4.8			
1806.9	2.7			
1845.4	6.3			7.9
1880.6	364	171	86.8	497
1891.6	4.9			
2203.3	4.4			5.6
2451.7	3.6			
2494.8	14.5		1.5	20
2581.8	3.0		1.1	
2642.2[b]	21.6			30

[a]The errors for these γ-ray energies are given in Table I.
[b]No coincidence information was obtained above this energy.

and in Fig. 4(b). Of the slices taken, these were the only ones that contained substantially useful information. Relative intensities from the integral coincidence spectra are included in Table II, and the results of the megachannel coincidence experiment are summarized in Table III.

An important gate that is missing from Fig. 4 is the one on the 329.5-keV γ ray, which depopulates the first excited state in Eu^{145}. Because of its position atop the intense $\gamma^{\pm}$ Compton edge, coincidence spectra gated on it, with or without intricate or nonintricate background subtraction, could not be "unconfused" from spectra indicating β^+ feeding. Unfortunately, this has ramifications on the construction of the decay scheme, as will be shown in Sec. IV.

3. Pair spectra. The two halves of the 8×8-in. NaI(Tl) split annulus were used in conjunction with the 7-cm^3 Ge(Li) detector to determine the relative amounts of β^+ feeding to the various levels in Eu^{145}. Each half of the annulus was gated on the 511-keV $\gamma^{\pm}$ peak and a triple coincidence (resolving time, $2\tau\approx100$ nsec) was required among these and the Ge(Li) detector. A resulting spectrum is shown in Fig. 5. Note that double-escape peaks are also enhanced in this spectrum. A discussion of the β^+ feedings extracted from this experiment is deferred until Sec. V, where they are presented in Table IV.

C. Half-Life Determination for Gd^{145g}

The half-life of Gd^{145g} was determined by following the net peak areas of the 1757.8- and 1880.6-

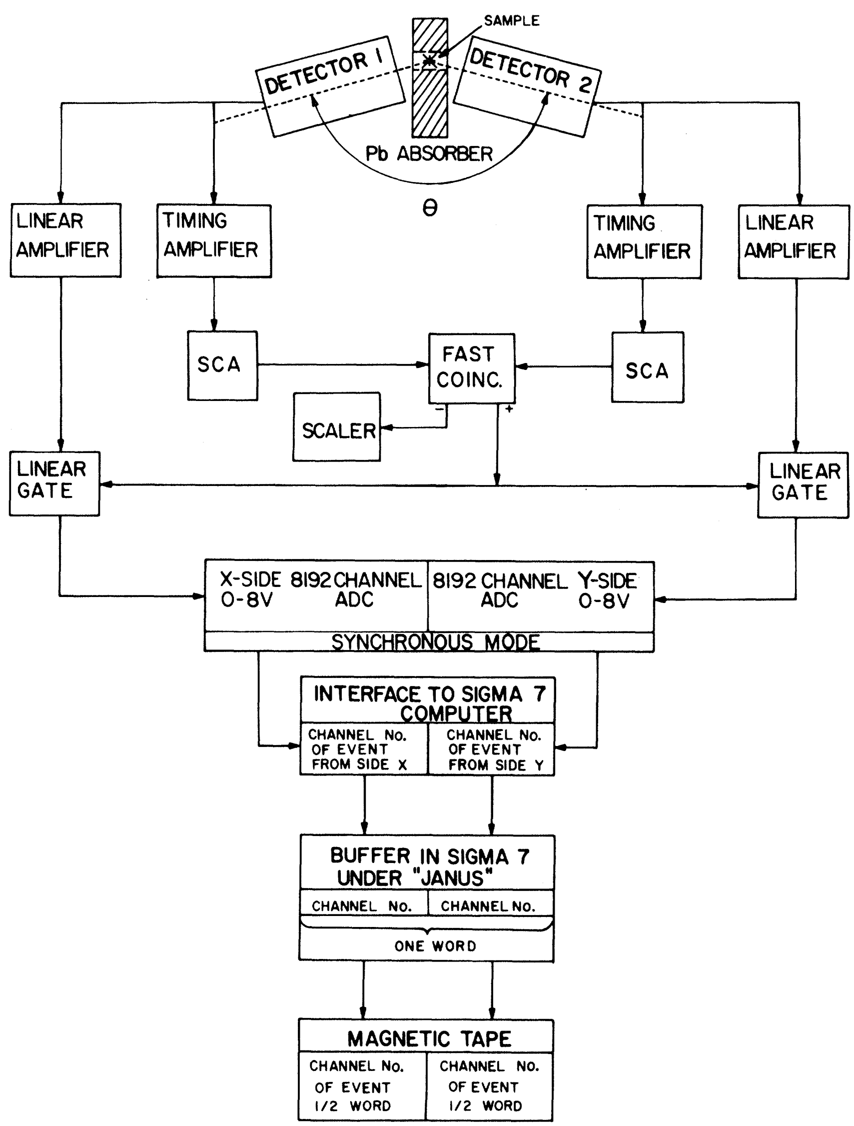
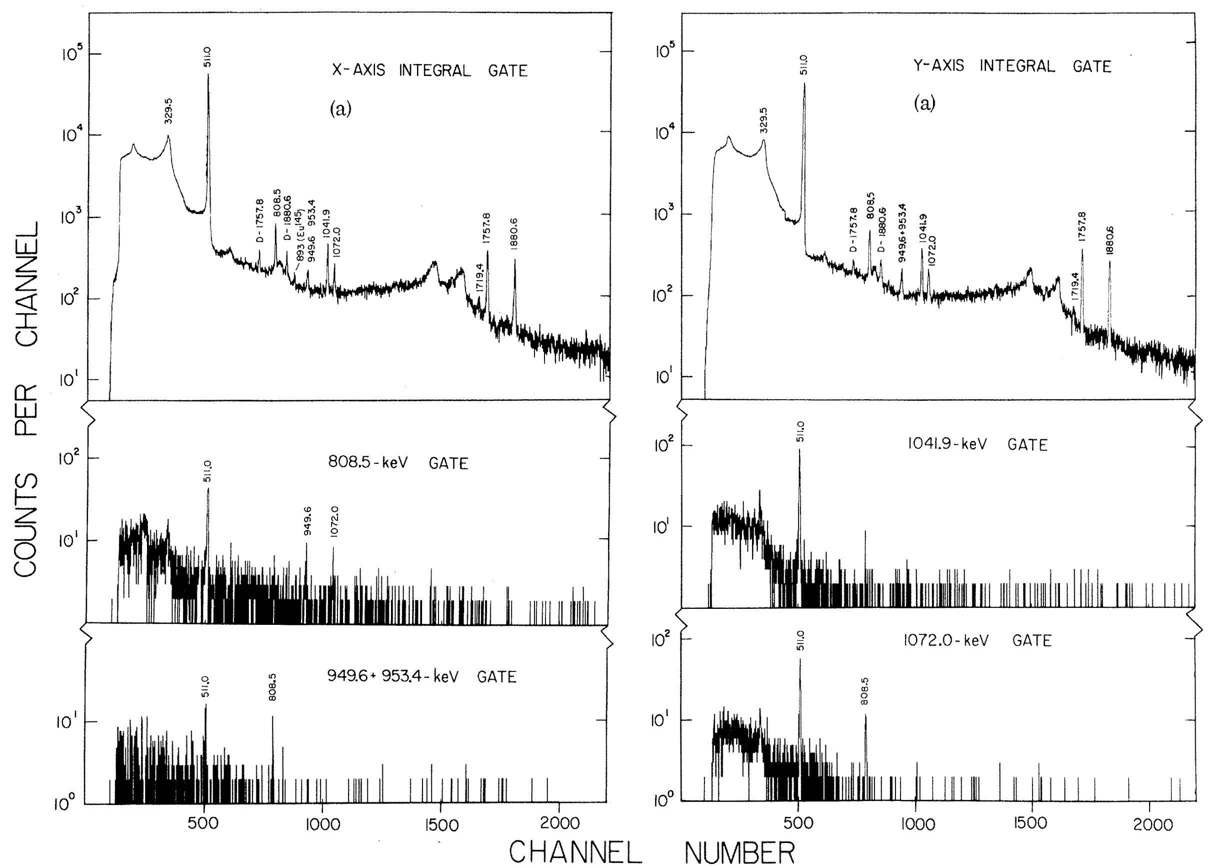


FIG. 3. Schematic diagram of the megachannel two-dimensional apparatus.

keV peaks as a function of time. We used a 50-MHz ADC interfaced to the MSU Cyclotron Laboratory Sigma-7 computer for this experiment. A code called GEORGE[20] allowed us to take data, have a live display on an 11-in. scope, and dump the displayed data onto the computer disk at precise intervals that were determined at the beginning of the run. The sequence of events: Count for the predetermined length of time, stop the counting, dump the spectrum onto the disk, erase the memory, and begin counting again. The entire dumping process takes significantly less than 1 sec. The



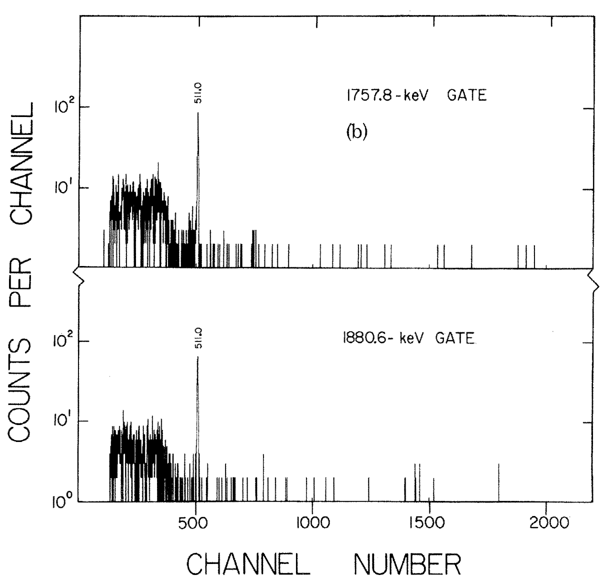


FIG. 4. Spectra from the two-dimensional megachannel coincidence experiment. The integral coincidence spectra are shown at the top of part (a), and various gated slices are shown in the remainder of (a) and in (b).

TABLE III. Summary of γ-ray coincidence in Gd^{145g}.

Gate energy (keV)	γ rays enhanced (keV)
Integral	329.5, 808.5, 949.6, 953.4, (1041.9),[a] 1072.0, 1719.4
808.5	949.6, 1072.0
949.6	
	808.5
953.4	
1041.9	(329.5),[b] (893.2)[c]
1072.0	(329.5),[b] 808.5
1757.8	$\gamma^{\pm}$
1880.6	$\gamma^{\pm}$
511-511	808.5, 1041.9, 1757.8, 1880.6 2494.8,[d] 2642.2[d]
Anti	1041.9, 1567.4, 1599.9, 1757.8, 1845.4, 1880.6, 2203.3, 2494.8, 2642.2

[a]As seen in Table II, the intensity for this transition is less than in singles. This is reasonable since it is only weakly fed by two γ transitions and β^+.

[b]This transition appears weakly in the gated spectrum.

[c]From Eu^{145} decay.

[d]This peak is very weak in the 511–511-keV spectrum.

TABLE IV. Comparison of experimental and theoretical $\epsilon(\text{tot})/\beta^+$ ratios for decay to states in Eu^{145}.

Energy[a] (keV)	$\epsilon(\text{tot})/\beta^+$ Experimental	Theoretical[b]
808.5	11	0.36
1041.9	1.6	0.65
1599.9	19	1.2
1757.8	≡1.4[c]	1.4
1880.6	1.7	1.7
2494.8	5.0	5.0
2642.2	12	7.1

[a]These are the only states in Eu^{145} that are measurably fed by β^+, as determined from the $\gamma^{\pm}$ gated coincidence spectrum.

[b]These values are only as precise as can be read from the graphs in Ref. 22.

[c]The experimental ratios were normalized to the theoretical ratios by assuming that the transition to the 1757.8-keV states is allowed and unhindered, presumably yielding the expected ratio.

spectra can be punched on cards later as they are removed from the disk, thereby making the start and stop times of data acquisition independent of the card punching time. A pulser peak was included in each spectrum so that dead-time corrections could be properly applied to the data. In this manner the half-life can be measured independently for any or all of the peaks in the entire spectrum.

Forty consecutive spectra were obtained for each of the two peaks at 1757.8 and 1880.6 keV, each one representing a 2-min time span. After background subtraction and dead-time corrections

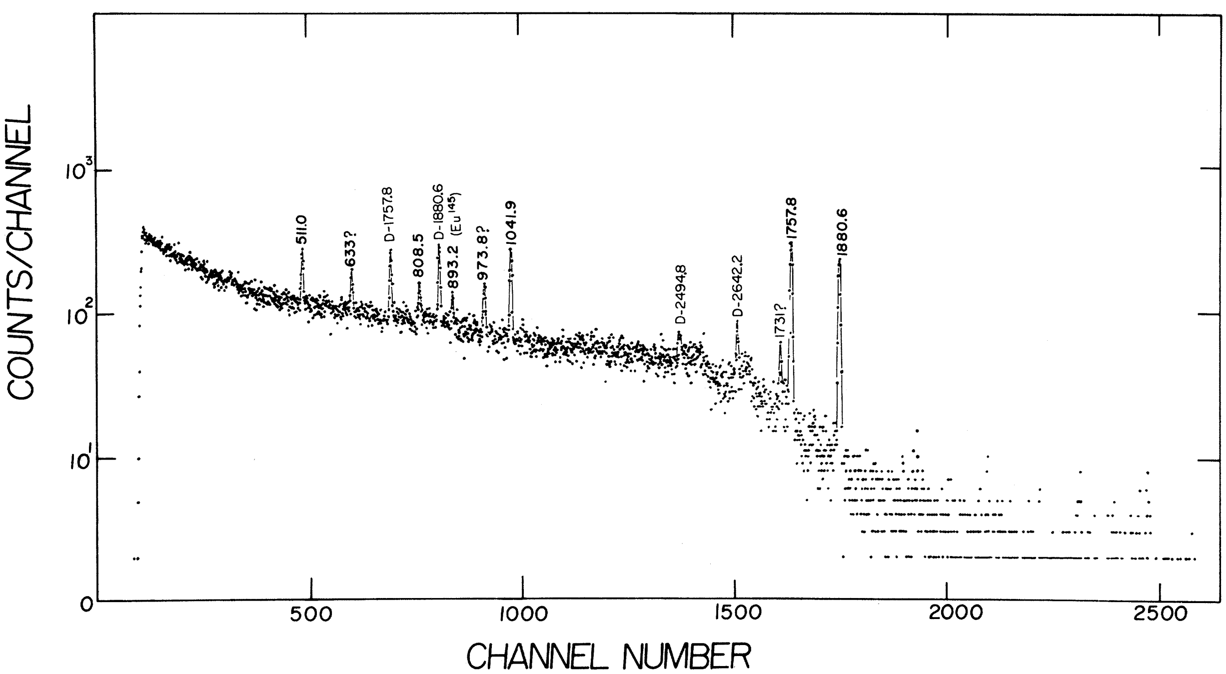


FIG. 5. Pair-coincidence spectrum showing the β^+ feedings from Gd^{145g} decay. This spectrum was recorded with a 7-cm^3 Ge(Li) detector operated in triple coincidence with the two halves of an 8×8-in. NaI(Tl) split annulus, each half of which was gated on the 511-keV region.

the points were least-squares-fitted with straight lines (semilog). From an average of these calculations we determined the half-life of Gd^{145g} to be 21.8 ± 0.6 min, to be compared with the less precise value of 25 min obtained by Grover.[3] (Examples of these spectra and half-life curves can be found in Eppley.[21])

IV. PROPOSED DECAY SCHEME

Our proposed decay scheme for Gd^{145g} is shown in Fig. 6. It is largely in agreement with the level scheme proposed by Newman *et al.*,[5] the main differences being our omission of their proposed levels at 2112.0, 2662.5, and 3167.2 keV and our addition of nine new levels at 953.4, 1567.3, 2203.3, 2642.2, 3236.0, 3259.6, 3285.6, 3623.8, and 4411.3 keV. Of the 38 γ rays listed in Table I, 28 have been placed in the decay scheme, accounting for over 97% of the total γ-ray intensity. It is entirely possible that many of the remaining γ rays proceed from levels that decay via a single transition. These γ rays were all too weak to have been seen in any of our coincidence work, so, with no further evidence for their placement, we have omitted them entirely.

The assigned spins and parities, discussed in Sec. V, represent a combination of deductions from our work and also the conclusions of Newman *et al.* for the states observed via the $Sm^{144}(\tau, d)Eu^{145}$ reaction. The results of the two studies are in good agreement for most states. We calculated[12] the total ϵ-decay energy to be $\simeq 5$ MeV. The β^+/ϵ ratios displayed on Fig. 6 are all calculated values using the methods of Zweifel.[22] We shall see later (cf. Table IV) that our experimentally deduced ratios for some of the more hindered

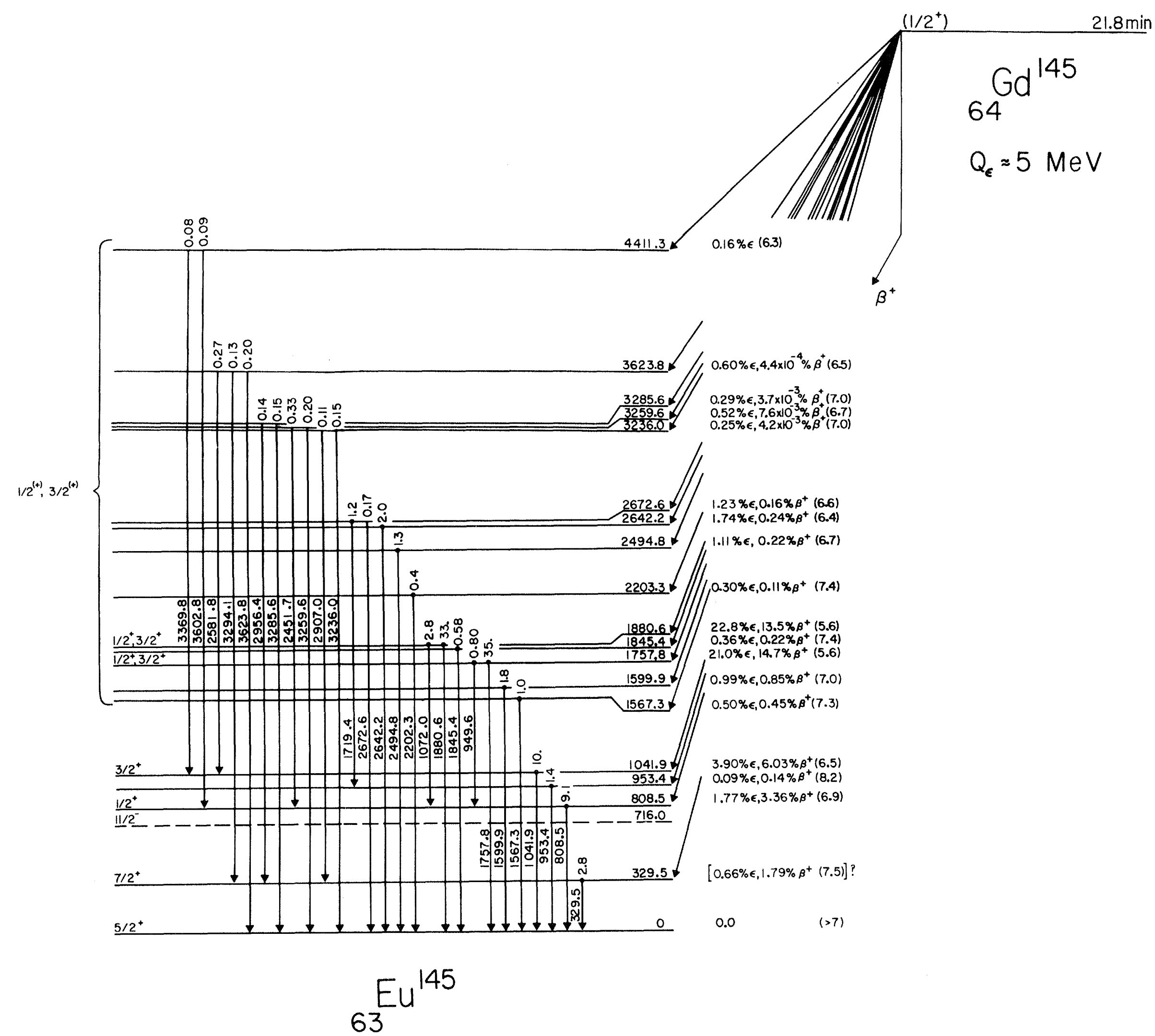


FIG. 6. Decay scheme of Gd^{145g}.

transitions do not agree with these values. However, we do not have experimental values for many of the states, and to be consistent we have used the calculated values. This does not alter any significant conclusions presented on the decay scheme.

The relative γ-ray intensities listed in Table I were based on a value of 100 for the 808.5-keV γ ray. The relative x-ray intensity was not measured. Thus, the intensities given on the decay scheme are based on the assumption that there is no direct β decay to the $Eu^{145}(d_{5/2})$ ground state. This seems to be a good assumption in several respects. First, in light of good evidence[2,5] for the ground state of Gd^{145} being predominantly an $s_{1/2}$ state, a direct transition to the Eu^{145} ground state would be a second-forbidden transition. Also, Newman *et al.* determined that the ≈25-min component of the $\gamma^{\pm}$ could be accounted for by assuming no β^+ decay to the ground state, based on the β^+/K x-ray value of 0.6 obtained by Grover.[3] (Note, however, that one has to be cautious here, for there does appear to be some decay to the 329.5-keV state that we cannot explain away.)

Specific evidence for the placement of levels and transitions in the decay scheme is given as follows:

Ground, 329.5-, 716.0-, 808.5-, and 1041.9-keV states. These states were all populated strongly by the $Sm^{144}(\tau, d)$ reaction and appear to be essentially single-particle states, viz., the $d_{5/2}$, $g_{7/2}$, $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$ in that order. We, too, see specific evidence for the 329.5-, 808.5-, and 1041.9-keV levels. The 716.0-keV state is the $\pi h_{11/2}$ isomeric state, which is not populated by the decay of Gd^{145g} but is populated by the decay[2] of Gd^{145m}.

As seen in the integral coincidence spectra of Fig. 4(a), the $\gamma^{\pm}$ Compton background peaks near the 329.5-keV γ ray, so no reliable information can be obtained from a gate on this γ ray. That it is indeed involved in cascades is indicated by the anticoincidence spectrum (Fig. 2), where its intensity is diminished. The four transitions into the 329.5-keV state were placed strictly on the basis of energy differences. From the intensity balances, we deduce that the 329.5-keV state receives 0.55% ϵ and 1.5% β^+ feeding. Also, the $\gamma^{\pm}$ coincidence spectrum (Fig. 5) shows the 329.5-keV γ ray. However, this much β^+/ϵ feeding implies a log*ft* of 7.5, which is much lower than reasonable considering that the transition to this state would most likely be a $\frac{1}{2}^+ \rightarrow \frac{7}{2}^+$, i.e., second-forbidden, transition. And, although the 329.5 lies in a particularly bad place for a precise intensity determination, we do not think that our intensity value (or that of Newman *et al.*) can be wrong enough to give us this low log*ft* value artificially. In addition, although we could have missed placing several γ rays that feed into the 329.5-keV level from above, the over-all intensity of the unplaced γ rays is rather small, so it would be difficult to alter the intensity balance by placing them. We are left with a β^+/ϵ feeding that we do not believe and cannot explain away easily.

The placement of the 808.5-keV γ ray as proceeding from a level of the same energy is consistent with our coincidence and anticoincidence data. The 949.6- and 1072.0-keV γ rays can be seen to be in coincidence with the 808.5-keV γ ray in Fig. 4(a). The 2451.7- and 3602.8-keV γ rays are too weak to be picked up in our coincidence spectra and were placed purely by energy differences. As we shall see in Sec. V, the 808.5-keV state is a $\frac{1}{2}^+$ state, which is consistent with its depopulating only to the ground state. The log*ft* of 6.9 is somewhat high for an allowed transition, but it falls within a reasonable range, and we shall see that the transition involves a multiparticle rearrangement, so it would be expected to be slow.

The 1041.9-keV γ ray can also be seen to be a ground-state transition, as it is enhanced in the anticoincidence spectrum. There are no strong coincidences in the 1041.9-keV gated spectrum (Fig. 4), again suggesting direct decay to the ground state. The 2581.8- and 3369.8-keV γ rays, too weak to be seen in our coincidence spectra, were placed solely on the basis of energy difference. The log*ft* for β^+/ϵ population of the 1041.9-keV state is quite in line with an allowed transition, consistent with the assignment of this state as $\frac{3}{2}^+$ by Newman *et al.*

1757.8- and 1880.6-keV states. The two intense γ rays at 1757.8 and 1880.6 keV dominate the entire Gd^{145g} γ-ray spectrum. They are enhanced in the anticoincidence spectrum and depressed in the integral coincidence spectra, and the spectra gated on them [Fig. 4(b)] show nothing other than $\gamma^{\pm}$. Thus, they are well established as ground-state transitions from levels having the same energies. Further, the 808.5-keV gated spectrum showed that each of these two states decays additionally through the 808.5-keV level. Together, these two states receive 72.6% of the total β^+/ϵ population from Gd^{145g}. The low log*ft* values (5.6 for each) certainly suggest allowed transitions, and, assuming the $\frac{1}{2}^+$ assignment for Gd^{145g}, this means that the states are $\frac{1}{2}^+$ or $\frac{3}{2}^+$. This is consistent both with their decaying directly to the ground state and through the $\frac{1}{2}^+$ 808.5-keV state. The 1757.8-keV state appears to be excited only slightly in the $Sm^{144}(\tau, d)$ reaction[5] and it is not clear whether the 1880.6-keV state is excited or not (it falls too close to the peak from the 1843-keV state). Needless to say, neither state appears to be simple in structure, and we shall explain both of them as three-quasiparticle states in the next section.

953.4- and 2672.6-keV levels. These levels were placed on the basis of moderately convincing, although by no means airtight, coincidence results. Both the 953.4- and the 1719.4-keV γ rays were enhanced in the integral coincidence spectra, neither was enhanced in the anticoincidence spectrum, and neither could be detected in the pair spectrum, implying that β^+ feeding could not account for their appearance in the coincidence spectra. Unfortunately, both are weak enough that the gated spectrum on the 949.6–953.4-keV region proved inconclusive. Additionally, the sum, 953.4 + 1719.4 = 2672.8 keV, so we place levels at 953.4 and 2672.6 keV, the order of the 953.4- and 1719.4-keV γ rays being chosen because of their relative intensities.

1567.3-, 1599.9-, 1845.4-, 2203.3-, 2494.8-, and 2642.2-keV levels. These levels were placed on the basis of their respective ground-state transitions being enhanced in the anticoincidence spectrum. Newman *et al.* also observed states at 1843 and 2480 (doublet) keV excited by the (τ, d) reaction.

The remaining levels: 3236.0, 3259.6, 3285.6, 3263.8, and 4411.3 keV. Because of the weakness of the γ rays, no coincidence data of any significance could be obtained above the line at 2642.2 keV. Thus, these four levels had to be placed solely on the basis of sums and must be considered as tentative. Under "normal" circumstances we would not venture to suggest levels on just this basis, but here there are mitigating circumstances. First, the precision on the sums is quite good, considering the energies and intensities involved: 0.5, 0.6, 0.3, 0.2, and 0.5 keV for the five levels, respectively. Second, the states are spaced rather widely apart in this nucleus with the γ rays having reasonably disparate energies. Such would tend to make accidental agreements less probable than under normal circumstances; yet it must be remembered that these are by no means random numbers, and there may be some subtle, insidious relations not recognized.

V. DISCUSSION

Some 20 states have now been placed, with varying degrees of confidence, in Eu^{145}. In some respects, then, this nucleus finds itself among the better known members of the $N = 82$ series. All five major proton orbits between $Z = 50$ and 82 lie reasonably close together, resulting in relatively low-lying single-particle states that are not so fragmented as some in the lighter $N = 82$ isotones. Also, the peculiar decay properties of Gd^{145g} give us some information about what appear to be three-quasiparticle states.

A. Single-Particle States

The five states at 0, 329.5, 716.0, 808.5, and 1041.9 keV comprise the major components of all of the single-proton orbits between $Z = 50$ and 82, viz., $d_{5/2}$, $g_{7/2}$, $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$, respectively. This was amply demonstrated by Newman *et al.*[5] in their (τ, d) scattering, where the spectroscopic factors indicated precisely the occupations expected for adding a proton to a $Z = 62$ nucleus.

The $\frac{5}{2}^+$ nature of the ground state is also corroborated by the decay properties[14] of Eu^{145} itself. The primary component of its wave function appears to be just what one might expect from a simple shell-model picture, $(\pi g_{7/2})^8 (\pi d_{5/2})^5$ above the closed $Z = 50$ shell. Note, now, that there is little or no β^+/ϵ decay ($\log ft \gtrsim 7$) from Gd^{145g} to this $\pi d_{5/2}$ ground state. Herein lies the first portion of the Gd^{145g} "strange case," for both Nd^{141g} and Sm^{143g} decay[9,10] quite readily ($\log ft \approx 5.3$) to the $\pi d_{5/2}$ ground states of their respective daughters, in simple shell-model terms these decays being $(\pi g_{7/2})^8 (\pi d_{5/2})^2 (\nu d_{3/2})^{-1} \rightarrow (\pi g_{7/2})^8 (\pi d_{5/2})$ and $(\pi g_{7/2})^8 (\pi d_{5/2})^4 (\nu d_{3/2})^{-1} \rightarrow (\pi g_{7/2})^8 (\pi d_{5/2})^3$. There are many ways in which one could explain away a milder retardation of the Gd^{145g} decay to the Eu^{145} ground state, but the only reasonable explanation that we find for the experimental facts (hindered by at least a factor of 100 and probably much greater) is that *the ground state of* Gd^{145} *is not a* $(\nu d_{3/2})^{-1}$ *state but instead a* $(\nu s_{1/2})^{-1}$ *state.* Newman *et al.* also come to this conclusion. Some reasonable indirect evidence for this is available, viz., the $(\nu s_{1/2})^{-1}$ state does progress to lower and lower energies with increasing Z in the $N = 81$ nuclei: It lies at 281 keV[23] in Ba^{137}, at 250 keV[23,24] in Ce^{139}, and at 195 keV[25] in Nd^{141}. Thus, it might be expected to have replaced the $(\nu d_{3/2})^{-1}$ state by the time Gd^{145} is reached. However, in our study[2] of Gd^{145m} we were neither able to confirm nor to deny this, so it must be admitted that the evidence is only indirect for this $s_{1/2}$ assignment. More will be said about it in the next section.

The $(\pi g_{7/2})^{-1}$ state [actually a $(\pi g_{7/2})^7 (\pi d_{5/2})^{2n} \ldots$ state – in the next section we shall see that the pairing force has undoubtedly removed some occupation from this orbit] at 329.5 keV is well established, but, quite surprisingly, it may receive a small amount of β^+/ϵ population, the $\log ft$ being ≈ 7.5. Actually, we do not believe this, and, considering the uncertainty in the intensity of the 329.5-keV γ ray because of its position in the spectrum, perhaps most of the feeding can be attributed to experimental difficulties. The results, however, are duly recorded on Fig. 6.

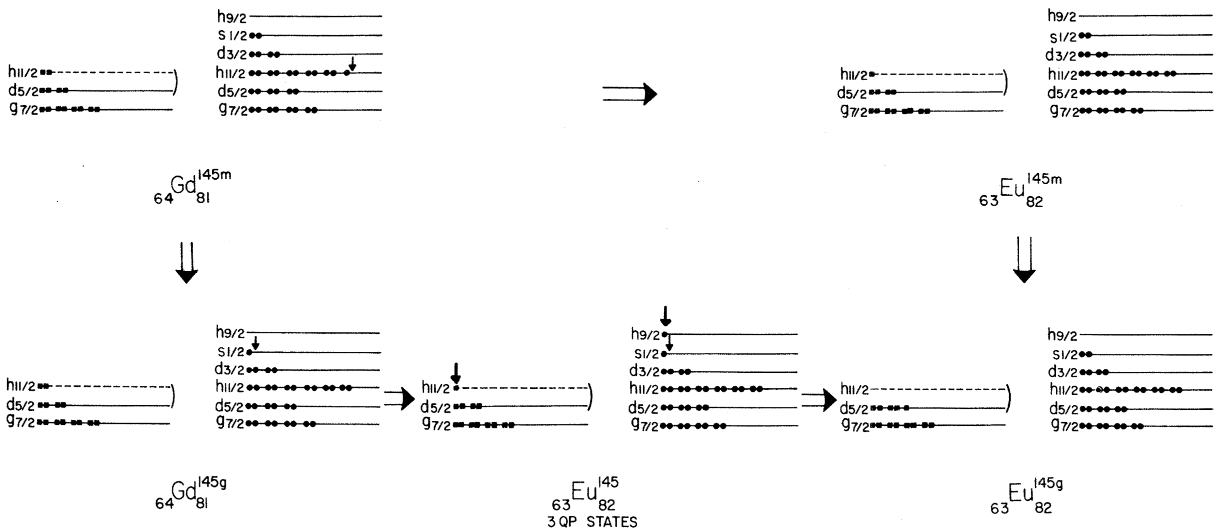


FIG. 7. Stylized representation of some important transitions in the Gd^{145}-Eu^{145} system. Protons are represented by squares and neutrons by circles. The arrows point out the particles or holes of particular interest for a given state.

As expected, the $h_{11/2}$ state at 716.0 keV is not populated by Gd^{145g} decay, although we noted[2] its being populated directly by 4.7% of the Gd^{145m} decay. The log*ft* was found there to be 6.2. The fact that such a direct decay takes place implies some occupation of the $h_{11/2}$ orbit by proton pairs in Gd^{145}. This is the second clue toward explaining the "strange case" of Gd^{145g}.

The β^+/ϵ decays to the $s_{1/2}$ 808.5- and $d_{3/2}$ 1041.9-keV states, with respective log*ft*'s of 6.9 and 6.5, appear to be allowed transitions. However, note that these are somewhat higher log*ft* values than those for unhindered allowed transitions in this nuclear region. This is dramatically illustrated by comparing them with the log*ft*'s for the transitions to the 1757.8- and 1880.6-keV states. The implication could be that the former transitions are not completely straightforward. Also, as can be seen in Table IV, the $\epsilon(\text{tot})/\beta^+$ ratios for decay to the 808.5- and 1041.9-keV states are large compared with the predicted[22] ratios for straightforward allowed transitions. Often such squelching of the β^+ branch is also an indication of complexities in the decay process. This is the third clue.

B. Three-Quasiparticle States

The fourth and most obvious clue, of course, is the strong decay of Gd^{145g} to the states at 1757.8 and 1880.6 keV. These two states account for 72% of the Gd^{145g} decay, and the low log*ft*'s, both 5.6, clearly indicate nonhindered allowed transitions. Now, the state at ≈1757 keV populated by an $l=2$ transfer (implying $I^\pi=\frac{3}{2}^+$) in the (τ, d) experiment of Newman *et al.* may or may not be the same as the 1757.8-keV state populated by Gd^{145g} decay. In any event, the extracted spectroscopic factor (C^2S) was only 0.02, indicating the structure of that state to be more complicated (or at least different) than what could be attained by a simple dropping of a proton into a vacant or semivacant Sm^{144} orbit. The 1880.6-keV state may or may not have been populated[26] (cf. Fig. 3 of Ref. 5) in the (τ, d) experiment, but if populated at all it was only to a very slight extent. Also, in their shell-model calculations using a truncated basis set (which considered only proton states and which did not allow more than a single particle to be excited from the $g_{7/2}$-$d_{5/2}$ subspace into the higher orbits), Newman *et al.* were unable to construct states corresponding to the 1757.8- and 1880.6-keV states. Our inference here is that perhaps these states involved the promotion of more than one proton into the $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$ region or, considering that the states lie well above the pairing gap, they involve broken neutron pairs.

We have arrived at a simple shell-model picture that, qualitatively at least, explains all four clues, or effects, quite well: (1) no β^+/ϵ feeding to the Eu^{145} ground state, (2) some direct feeding of the 716.0-keV state by Gd^{145m}, (3) hindered transitions to the $s_{1/2}$ and $d_{3/2}$ states, and (4) fast transitions to the 1757.8- and 1880.6-keV states – meaning that these last go by major components of the wave functions and not by minor admixtures. Our model is outlined in stylized form in Fig. 7 and involves two assumptions: (1) The ground state of Gd^{145} is indeed a $(\nu s_{1/2})^{-1}$ state, and (2) there is appreciable occupation of the $h_{11/2}$ orbit by proton pairs in both

Gd^{145g} and Gd^{145m}. Both assumptions have already been discussed implicitly, and (2) has been directly demonstrated by the population of the 716.0-keV $h_{11/2}$ state by Gd^{145m} (cf. the appropriate transition in Fig. 7). (Also, compare the rapid drop in position of the $h_{11/2}$ orbit from 1.1 MeV in Pr^{141} to 716.0 keV in Eu^{145}. It should lie even lower in Gd^{145}, and the pairing force should insure its partial occupation simply by virtue of its large degeneracy.)

Now, there are well-documented cases of β^+/ϵ decay into high-lying three-quasiparticle states from the nearby nuclei Nd^{139m} (Ref. 9 and McHarris, Beery, and Kelly[27]) and Sm^{141m} (Ref. 13), both of which follow quite straightforwardly from simple shell-model considerations. Looking about for an analogous set of transitions, one is immediately struck by the availability of the $\nu h_{9/2}$ orbit – by a crude extrapolation down from the lead-bismuth region we would predict it to lie somewhere between 1 and 2 MeV higher than the $s_{1/2}$ or $d_{3/2}$ orbits. Thus, the primary decay of Gd^{145g} can be represented as $\pi h_{11/2} \rightarrow \nu h_{9/2}$, or more completely, $(\pi h_{11/2})^{2n}(\nu s_{1/2})^{-1} \rightarrow (\pi h_{11/2})^{2n-1}(\nu h_{9/2})(\nu s_{1/2})^{-1}$. This would make the 1757.8- and 1880.6-keV states three-quasiparticle states having the primary configuration $(\pi h_{11/2})(\nu h_{9/2})(\nu s_{1/2})^{-1}$.

This model also explains the hindrance of the β^+/ϵ decay to the 808.5- and 1041.9-keV states. Each would require, in addition to the unfavorable transformation of an existing (high-spin) proton into an $s_{1/2}$ neutron, a promotion of the remaining proton from that pair into a higher orbit. Thus, the observed transitions probably proceed primarily through admixtures.

Appealing though it be, this explanation must at this time remain a hypothesis, for we have no direct proof of (1) the $(\nu s_{1/2})^{-1}$ nature of Gd^{145g} and (2) the fact that it is specifically the $\nu h_{9/2}$ orbit that participates in the three-quasiparticle states. Information would be useful concerning Dy^{147m+g}, the next member of the series, but it is far enough from stability to present formidable production difficulties. The same is true for Tb^{145}, which could populate states in Gd^{145}. Perhaps most promising is the study of Gd^{145} states via the $Sm^{144}(\tau, 2n\gamma)$ reaction.

C. Remaining States

Relatively little can be deduced about the remaining states at this time. The 953.4-keV state is anybody's guess. Although placed by reasonably convincing coincidence data, we have no clues as to its structure. The remaining states are all populated by transitions having log*ft*'s variously in the allowed or fast first-forbidden range. Thus, they are all probably $\frac{1}{2}$ or $\frac{3}{2}$ states, with the majority having even parity. One word about the 1599.9-keV state: We observe its being populated by the Gd^{145g} decay, which implies a $\frac{1}{2}$ or $\frac{3}{2}$ assignment. This is incompatible with the $\frac{7}{2}^+$ assignment by Newman *et al.*, but they[26] consider the statistics in their angular distribution for this state to be poor enough to make that assignment somewhat questionable anyway.

D. ϵ/β^+ Ratios

From our $\gamma^{\pm}$ gated spectrum (Fig. 5) we obtained the relative β^+ feedings to seven of the Eu^{145} states. The deduced ϵ/β^+ ratios for the transitions to these states are listed in Table IV, where they are compared with the theoretical ratios calculated by Zweifel's methods.[22] We normalized the experimental values to the theoretical values with the transition to the 1757.8-keV state, which we consider to be one of the two most straightforward transitions in the entire decay scheme. (If one normalizes to, say, the 808.5-keV state, then the β^+ feeding to the other states quickly exceeds 100%.) It can be seen that the ϵ/β^+ ratio appears to be a fairly sensitive indicator of the degree of hindrance of a transition, for it does not take much to depress the β^+ branch. Unfortunately, the entire theoretical consideration of ϵ/β^+ ratios versus forbiddenness or hindrance needs serious overhauling now, so little can be said in a quantitative sense.

ACKNOWLEDGMENTS

We thank H. Hilbert and Dr. H. Blosser for their aid and instruction in the operation of the MSU cyclotron. We also thank R. Todd for his aid in the acquisition of some of the data, and Dr. B. H. Wildenthal for very helpful discussions on the nature of nuclear states near $N=82$ and for his critical reading of the manuscript.

---

*Work supported in part by the U. S. Atomic Energy Commission.

†Work supported in part by the U. S. National Science Foundation.

[1] R. E. Eppley, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C 2, 1077 (1970).

[2] R. E. Eppley, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C, 2, 1929 (1970).

[3]J. R. Grover, Phys. Rev. 116, 406 (1959).
[4]J. Olkowsky, M. LePape, I. Gratot, and L. Cohen, J. Phys. Radium 20, 549 (1959).
[5]E. Newman, K. S. Toth, R. L. Auble, R. M. Gaedke, M. F. Roche, and B. H. Wildenthal, Phys. Rev. C 1, 1118 (1970).
[6]See, e.g., K. S. Toth, E. Newman, B. H. Wildenthal, R. L. Auble, R. M. Gaedke, and M. F. Roche, in Proceedings of the International Conference on Radioactivity in Nuclear Spectroscopy, Vanderbilt University, Nashville, Tennessee, 11–15 August 1969 (Gordon and Breach, Science Publishers, Inc., New York, to be published), and the comments following.
[7]J. Felsteiner and B. Rosner, Phys. Letters 31B, 12 (1970).
[8]J. S. Geiger, R. L. Graham, I. Bergström, and F. Brown, Nucl. Phys. 68, 352 (1965).
[9]D. B. Beery, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. 171, 1283 (1968).
[10]D. DeFrenne, K. Heyde, L. Dorikens-Vanpraet, M. Dorikens, and J. Demuynck, Nucl. Phys. A110, 273 (1968).
[11]D. B. Beery, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. 188, 1851 (1969).
[12]W. D. Myers and W. J. Swiatecki, University of California Lawrence Radiation Laboratory Report No. UCRL-11980, 1965 (unpublished).
[13]For the properties of Sm^{141m+g}, see R. E. Eppley, R. R. Todd, R. A. Warner, Wm. C. McHarris, and W. H. Kelly, to be published; partially summarized by R. E. Eppley, Michigan State University Nuclear Chemistry Annual Report for 1969, No. COO-1779-13 (unpublished).
[14]I. Adam, K. S. Toth, and M. F. Roche, Nucl. Phys. A121, 289 (1968).
[15]J. T. Routti and S. G. Prussin, Nucl. Instr. Methods 72, 125 (1969). We used a variant of this code adapted for the MSU Cyclotron Laboratory Sigma-7 computer by T. Arnette, C. Merritt, and W. H. Kelly.
[16]R. E. Doebler, G. C. Giesler, and K. L. Kosanke, unpublished.
[17]R. L. Auble, D. B. Beery, G. Berzins, L. M. Beyer, R. C. Etherton, W. H. Kelly, and Wm. C. McHarris, Nucl. Instr. Methods 51, 61 (1967).
[18]EVENT RECOVERY, a program written for the MSU Cyclotron Laboratory Sigma-7 computer by D. Bayer, D. B. Beery, and G. C. Giesler.
[19]G. C. Giesler, Wm. C. McHarris, R. A. Warner, and W. H. Kelly, to be published.
[20]GEORGE, a data-taking code with live oscilloscope display developed by P. Plauger.
[21]R. E. Eppley, Ph. D. thesis, Michigan State University, 1970 (unpublished).
[22]P. F. Zweifel, Phys. Rev. 96, 1572 (1954); 107, 329 (1957); and presented graphically in C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, New York, 1967) 6th ed., p. 575.
[23]R. H. Fulmer, A. L. McCarthy, and B. L. Cohen, Phys. Rev. 128, 1302 (1962).
[24]E. I. Biryukov, V. T. Novikov, and N. S. Shimanskaya, Izv. Akad. Nauk SSSR, Ser. Fiz. 27, 1408 (1963) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 27, 1383 (1963)].
[25]F. Yap, R. R. Todd, W. H. Kelly, and Wm. C. McHarris, to be published.
[26]B. H. Wildenthal, Michigan State University, private communication.
[27]Wm. C. McHarris, D. B. Beery, and W. H. Kelly, Phys. Rev. Letters 22, 1191 (1969).