Spectroscopic Investigation of Even-Even Neutron-Deficient Gd Isotopes*

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Properties of levels in ^{146}Gd, ^{148}Gd, and ^{150}Gd have been investigated both by observing the electron-capture decay of ^{148}Tb and ^{150}Tb as well as the γ transitions following the (α, xn) reactions on ^{144}Sm and ^{148}Sm targets. Decay schemes were constructed or confirmed. The angular distributions of the γ lines with respect to the beam direction enabled spin assignments for most states. Searches for isomerism revealed lifetimes of $T_{1/2} = 17.3 \pm 2.0$ nsec and $T_{1/2} = 9.1 \pm 2.0$ nsec, respectively, for the 8^+ 2689-keV level in ^{148}Gd and the 6^+ 2981-keV state in ^{146}Gd and indicate a particle character for these states. An upper limit of 5 nsec was derived for the half-lives of any level reached in ^{150}Gd. The decay schemes of ^{148}Gd and ^{150}Gd are similar to those of the neighboring neutron-deficient nuclei, e.g. ^{148}Sm and ^{146}Nd. The low-lying negative-parity states observed may represent a collective sequence based on a 3^- state.

I. INTRODUCTION

The heavier Gd isotopes exhibit properties characteristic of strongly deformed nuclei. The ground-state collective sequence of these nuclei have been observed to high-spin states[1] and rotational properties are indicated. Also quasi-β-bands are observed (for ^{152}Gd see e.g. Ref. 2). The shell closure at 82 neutrons occurs for ^{146}Gd; this nucleus is expected to have spherical nuclear shape. Thus, the lighter Gd isotopes are ideal for studies of nuclei lying in a transition region between a rotational regime and a shell closure.

We undertook a systematic investigation of lighter even-even Gd nuclei using both in-beam and radioactive γ spectroscopy. Excitation functions, angular distributions, and megachannel γ-γ-t coincidences have been undertaken. Some results of these investigations based entirely on singles γ spectra have been reported earlier.[3]

During our investigations we have learned about a number of similar experiments (Refs. 4–11). Among the most recent are a study on ^{150}Gd by Haenni, Sugihara, and Bowman[9] following the decay of ^{150m}Tb, as well as recent prepublication reports by Kownacki *et al.*[10] on ^{146}Gd and by Hashizume, Tendow, and Katou[11] on ^{148}Gd.

II. EXPERIMENTAL PROCEDURES AND RESULTS

For the radioactive spectroscopy natural Eu_2O_3 was bombarded with 65-MeV ^{3}He beams from the Princeton AVF cyclotron. The radioactive samples containing the ^{148}Tb and ^{150}Tb were separated using the Princeton isotope separator. The sections of Al collecting foils at mass numbers 148 and 150 were then used directly as sources for our Ge(Li) γ spectrometers, which had energy resolutions of approximately 5 keV at ^{60}Co energies. In order to distinguish the γ lines following the decays of ^{148}Tb ($T_{1/2} = 70$ min) and ^{150}Tb ($T_{1/2} = 3.1$ h), consecutive γ spectra were taken at time intervals of 40 and 160 min, respectively. Energy and intensity calibrations were made before the runs by recording spectra of standard radioactive sources. In Tables I and II we list energies and relative intensities of those γ lines that have been assigned to ^{150}Gd and ^{148}Gd, respectively, on this basis. Typical γ spectra are shown in Figs. 1 and 2.

In order to place the observed γ transitions into a decay scheme, coincidence information is clearly needed. Attempts to obtain coincidence spectra out of beam failed due to insufficient intensity of the mass-separated sources. Coincidence relations were established from the in-beam experiments (see below). For in-beam spectroscopy isotopically enriched samarium oxide targets of thickness 10 mg/cm^2 were used. The samarium oxide was dispersed in polystyrene and then placed on Formvar backings. The targets were irradiated with beams of α particles at a current of less than 3 nA. The resulting γ radiations were detected in Ge(Li) detectors of 5% efficiency having a system energy resolution of less than 3 keV full width at half maximum (FWHM) at ^{60}Co energies. The electronics were of standard commercial type. Intensity and energy calibrations were obtained by recording spectra of standard radioactive sources. In order to distinguish the γ transitions between levels of the even Gd isotopes from competing reactions and background lines, singles spectra were taken at several beam energies between 24 and 56 MeV. The detector for these runs was placed at 90° with respect to the beam line. Examples of these spectra from ^{150}Gd, ^{148}Gd, and ^{146}Gd are shown in Figs. 3–5. The γ transitions assigned on this basis to the even Gd isotopes are labeled in these figures and their energies and relative intensities are listed in Tables I–III. The errors are estimated to be about 0.5 keV and 10%, respectively. Even at beam energies of 56 MeV we could not detect any lines with appreciable intensity that could be assigned to ^{144}Gd. We therefore suspect that the line at 921 keV initially reported[3] for ^{144}Gd has been mistaken with the 924-keV line in ^{145}Gd.

In order to obtain information about the multipolarities of the γ lines and spin values, we recorded singles γ spectra at six angles between 30 and 105° relative to the beam direction. For these measurements we placed the detector 15 cm away from the targets. The measurements at 30° were taken at a position where the γ rays had to penetrate a thicker part of the Al wall of the scattering chamber. This resulted in an energy-dependent reduction of the γ-line intensities. Therefore, an empirical correction taking the difference in wall thickness into account was applied in order to derive intensities that could be compared to those obtained at the remaining positions. This correction amounts to less than 10% for the most seriously affected 40-keV Sm K x rays, which were used to normalize all spectra to each other. Our measurements for $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions resulted in the expected values. Therefore confidence in all our angular-distribution coefficients seems justified. Plots of the angular distributions thus observed are shown in Figs. 6–8. The experimental values are indicated by the error bars while the solid lines represent the results of the least-squares fits to the angular-distribution function

$$W(\theta) = 1 + A_2/A_0 P_2(\cos\theta) + A_4/A_0 P_4(\cos\theta).$$

The values A_2/A_0 and A_4/A_0 are listed in Tables I–III. These experimental coefficients commonly

TABLE I. γ transitions assigned to ^{150}Gd.

Energy (keV)	Intensity from ^{150}Tb decay	Intensity at 30-MeV α	Angular-distribution coefficients A_2/A_0	Angular-distribution coefficients A_4/A_0
~95		a		
146.2		1.7		
~160		a		
183.6		7.5	0.40 ± 0.40	−0.02 ± 0.40
196.6		11.1	0.38 ± 0.12	0.07 ± 0.18
237.6		4.1	0.32 ± 0.20	0.02 ± 0.30
274.5		3.9	−0.34 ± 0.28	0.10 ± 0.40
342.6		4.0	−0.59 ± 0.20	−0.21 ± 0.29
404.2		10.3	−0.77 ± 0.12	0.07 ± 0.16
412.4	1.2	21.2	−0.26 ± 0.07	−0.02 ± 0.10
~415		b		
438.4	1.7	6.8	0.37 ± 0.14	−0.05 ± 0.20
454.9		8.0	−0.23 ± 0.10	−0.10 ± 0.14
496.5	19.0	51.8	−0.12 ± 0.06	0.04 ± 0.08
~511		c		
550.9	11.0		0.01 ± 0.12	0.00 ± 0.17
566.9	5.3	31.2	0.29 ± 0.07	−0.06 ± 0.10
606.8		30.0	0.37 ± 0.06	−0.01 ± 0.10
622.7		10.4	0.09 ± 0.10	0.08 ± 0.16
638.5	100.	100.	0.32 ± 0.08	−0.03 ± 0.12
650.1	5.1	79.0	0.48 ± 0.08	0.09 ± 0.06
734.8		5.5		
792.8	6.1			
828.3		9.2	0.58 ± 0.10	−0.04 ± 0.16
880.3	4.2			
1017.2		4.1		
1429.4	3.0			
1517.3	5.2			

[a] Only observed in coincidence spectra.
[b] Not separated from 412.4.
[c] Not separated from annihilation radiation.

are smaller than theory predicts for several reasons: incomplete alignment by the reaction, unobserved intermediate transitions, attenuations due to hyperfine interactions in longer living states. However, from the signs of these coefficients, particularly of the A_2/A_0, the general shape of the distribution and the actual magnitude compared to that of, e.g., the $2^+ \to 0^+$ ground-state transitions dipole or quadrupole character can be distinguished quite reliably.

For γ-γ-t in-beam coincidence experiments we constructed a special small scattering chamber. Two Ge(Li) detectors at 90° with respect to the beam direction face each other and can be placed as close as 1.5 cm to the beam spot on target. With our Ge(Li) spectrometers and employing commercial constant fraction timing discriminators we were able to obtain FWHM time resolutions of order of 20 nsec with pulses in both detectors corresponding to energies above 100 keV. For coincident events, the time relationship and the energies of the two γ rays in both spectrometers were serially recorded on magnetic tape employing a Sigma 2 computer as buffer. Coincidence spectra for selected γ transitions were subsequently obtained by sorting the events stored on the magnetic tapes with the appropriate time and energy gates set. Sample spectra thus obtained are shown in Figs. 9–11. Coincidences due to Compton events have been corrected for by subtracting spectra obtained with gates set on flat portions of the spectra near the photopeaks of lines of interest. Random coincidences are almost negligible. The results of our coincidence experiments are given in Tables IV–VI. For convenience we only give rounded energies. Also it

TABLE II. γ transitions assigned to ^{148}Gd.

Energy (keV)	Relative intensities from ^{148}Tb decay	Relative intensities at 48-MeV α	Angular-distribution coefficients A_2/A_0	Angular-distribution coefficients A_4/A_0
122.8		4.5	0.84 ± 0.36	1.04 ± 0.54
131.5		9.0	0.41 ± 0.09	0.32 ± 0.13
~140		a		
182.0		a		
~198		a		
204.3		a		
214.4		a		
~224		a		
238.5	2.0			
279.1		11.8	-0.26 ± 0.08	-0.01 ± 0.12
309.0		a		
330.0		a		
335.7		a		
394.9	5.6	37.8	0.26 ± 0.04	-0.01 ± 0.05
412.7		a		
~455		a		
481.0		18.4	0.18 ± 0.08	0.07 ± 0.12
489.0	23.6	26.1	-0.08 ± 0.06	0.07 ± 0.08
526.0		7.1	-0.00 ± 0.11	0.07 ± 0.16
573.1		a		
631.0	27.0	50.5	0.27 ± 0.04	0.01 ± 0.04
660.6		11.8	0.56 ± 0.10	-0.07 ± 0.14
~751		a		
782.6	100.	100	0.26 ± 0.03	-0.02 ± 0.04
807.4		18.2	0.39 ± 0.06	-0.07 ± 0.08
879.8		22.8	0.31 ± 0.06	0.00 ± 0.08
1010.6	2.4	11.4	0.51 ± 0.10	0.11 ± 0.16
1078.9	12.8			
1083.		4.6	0.56 ± 0.21	0.17 ± 0.34
1121.2	2.2	5.7	0.50 ± 0.26	0.51 ± 0.40
~1310		a		
1491.	5.5			
1592.	7.6			
1863.	7.9			
2104.	6.8			

[a] Weak: have only been observed in prompt or delayed coincidence with beam burst of cyclotron and other γ transitions, where background is lower than in singles spectra.

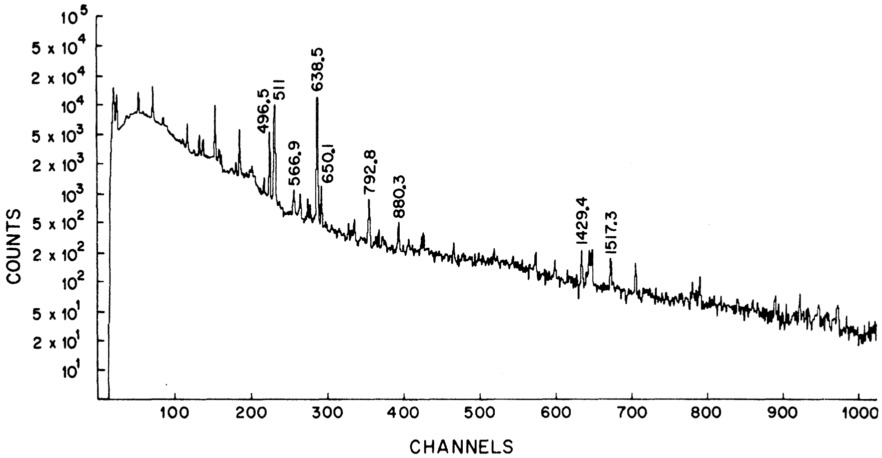

FIG. 1. Singles γ spectrum of the decay of ^{150}Tb to ^{150}Gd. Transitions assigned to ^{150}Gd are labeled by their energy.

should be noted, coincidences involving the 511-keV line could be in error due to difficulties in the subtraction process due to the intense annihilation radiation.

Searches for isomeric states were performed by starting a time-to-amplitude converter with the observed γ rays and stopping it with a signal from the radio frequency generator of the cyclotron. The radio frequency depended on the α-particle energy and was about 20 MHz. γ spectra detected with the Ge(Li) spectrometer were then accumulated in eight different parts of the computer memory according to the time relationship of the observed γ ray with respect to the arrival time of the beam bursts on target. The time resolution obtained in these experiments varied somewhat with the γ-ray energy but typically was of the order of FWHM = 10 nsec. For ^{150}Gd no γ transitions delayed with respect to the arrival time of the beam bursts were recorded. We therefore place an upper limit for isomerism in ^{150}Gd at 5 nsec. In Figs. 12 and 13 we show plots of decay curves for γ lines assigned to ^{148}Gd and ^{146}Gd. In both figures $T = 0$ is not the time of arrival of the beam burst. For ^{148}Gd, data for large delay times and no prompt events have been accumulated. For ^{146}Gd the apparent shifts of the time zero points for the different decay curves can be attributed to the fact that pulses of lower energy cross the discriminator level at later times. Also long level lifetimes produce similar effects. Evaluating the slopes of the decay curves we deduce the isomeric levels $T_{1/2} = 17.3 \pm 2.0$ nsec for ^{148}Gd and $T_{1/2} = 9.1 \pm 2.0$ nsec for ^{146}Gd. Since the accepted time range of the time-to-amplitude converter covered less than one interval between beam bursts, time calibrations had to be obtained using delay line cables. The quoted errors are

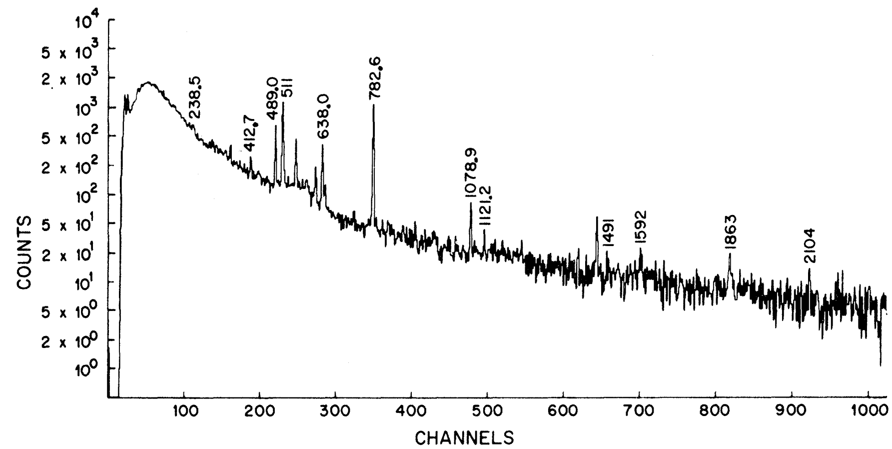

FIG. 2. Singles γ spectrum of the decay of ^{148}Tb to ^{148}Gd. Transitions assigned to ^{148}Gd are labeled by their energy.

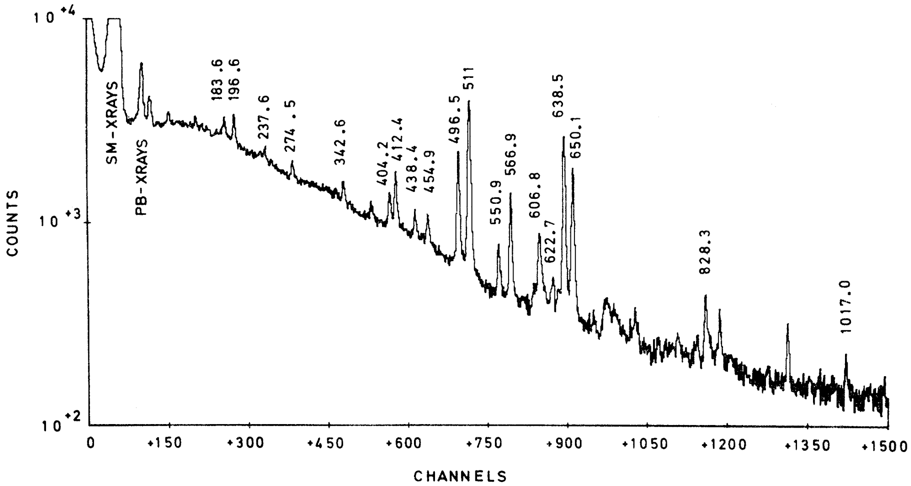

FIG. 3. Singles γ spectrum from ^{148}Sm(30-MeV $\alpha, 2n\gamma$)^{150}Gd reaction. Transitions assigned to ^{150}Gd are labeled by their energy.

due both to uncertainties in the time calibrations and apparent experimental systematic deviations, especially in the cases of the 395- and 489-keV γ lines in ^{148}Gd. No other γ lines assigned to ^{148}Gd apart from those shown in Fig. 12 were observed to be delayed with respect to the beam bursts excepting the 807.4-keV line, which seems to be almost constant within the 50-nsec time range. Since we observe a 808-keV background line also in experiments with various targets, we assume that the delayed 808-keV events are probably due to this background line. For this reason the quoted intensity for the 807.4-keV transition in Table II is probably overestimated. In a different run, where the prompt γ rays were also recorded, we observe that the γ transitions in ^{148}Gd at 279.1, 526.0, and 660.0 keV are prompt within our resolving time. For ^{146}Gd sorts of our γ-γ-t coincidence data were performed by setting a ~30-nsec-wide gate on the time spectrum roughly 30 nsec away from the prompt curve. Examples of the delayed coincidence spectra thus obtained are shown in Fig. 14. The observed delayed coincidence relationships are listed in Table VII.

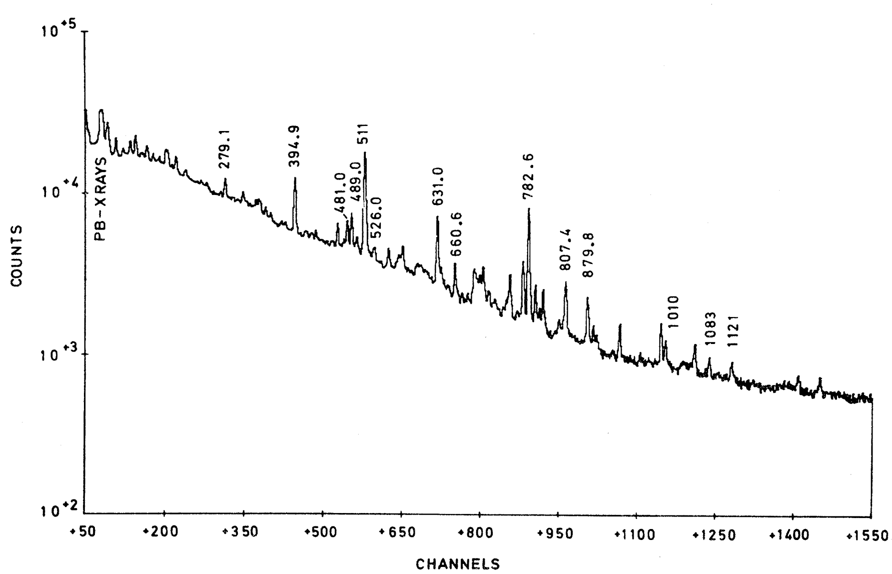

FIG. 4. Singles γ spectrum from ^{148}Sm(48-MeV $\alpha, 4n\gamma$)^{148}Gd reaction. Transitions assigned to ^{148}Gd are labeled by their energy.

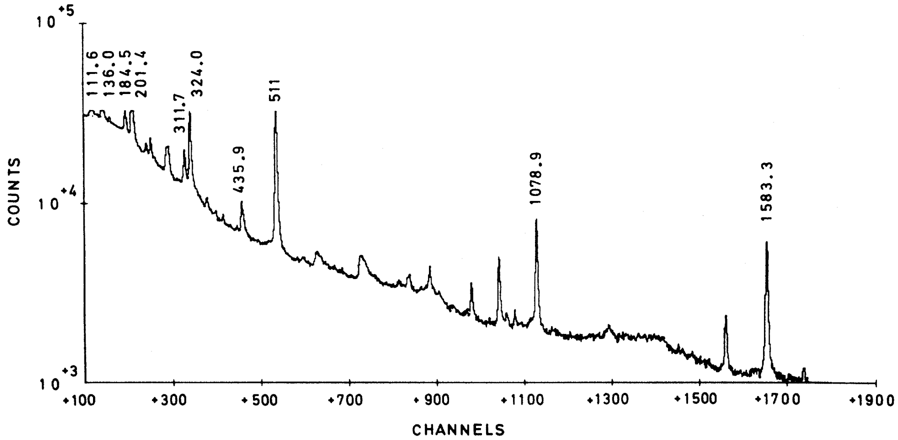

FIG. 5. Singles γ spectrum from ^{144}Sm(30-MeV α, $2n\gamma$)^{146}Gd reaction. Transitions assigned to ^{146}Gd are labeled by their energy.

III. DECAY SCHEMES

The decay schemes constructed on the basis of the experimental evidence presented in the previous section are shown in Figs. 15–17. The main schemes in Figs. 15 and 16 result from our in-beam work, while the schemes in the lower left-hand side reflect our studies of the ^{150}Tb and ^{148}Tb decays. The dots at the ends of the arrows representing the γ transitions indicate observed coincidence relationships. Spin assignments are based on our angular-distribution data (see below), which were compared to the tables of Yamazaki.[12] While generally the construction of these decay schemes on the basis of the coincidence experiments and the observed intensity and energy relationships is straightforward, some details ought to be mentioned.

A. ^{150}Gd

As far as the placing of the stronger transitions up to excited levels at 1701 keV is concerned, agreement between different investigations[7-9] generally exists both from in-beam studies and experiments with the ^{150}Tb decay. In the construction of the total decay scheme for ^{150}Gd, we are in agreement with Haenni, Sugihara, and Bowman[9] except for a few minor differences. Haenni, Sugihara, and Bowman[9] employed detectors with a somewhat superior energy resolution than achieved in our in-beam studies. They observed a doublet of γ lines at 648.4 and 650.4 keV, which we do not separate. This explains our observation of self-coincidences of the 650-

TABLE III. γ transitions assigned to ^{146}Gd.

Energy (keV)	Relative intensity at 30-MeV α	Angular-distribution coefficients A_2/A_0	A_4/A_0
111.6	a		
136.0	21.2	0.01 ± 0.05	0.06 ± 0.15
201.4	22.7	0.27 ± 0.06	-0.05 ± 0.09
311.7	21.7	0.16 ± 0.04	0.11 ± 0.06
324.0	64.0	0.29 ± 0.03	0.04 ± 0.05
435.9	12.8	0.11 ± 0.08	0.10 ± 0.12
1078.9	85.5	0.26 ± 0.03	-0.02 ± 0.04
1583.3	100.0	0.34 ± 0.03	-0.03 ± 0.05

[a] Disturbed by 111-keV line in ^{147}Gd.

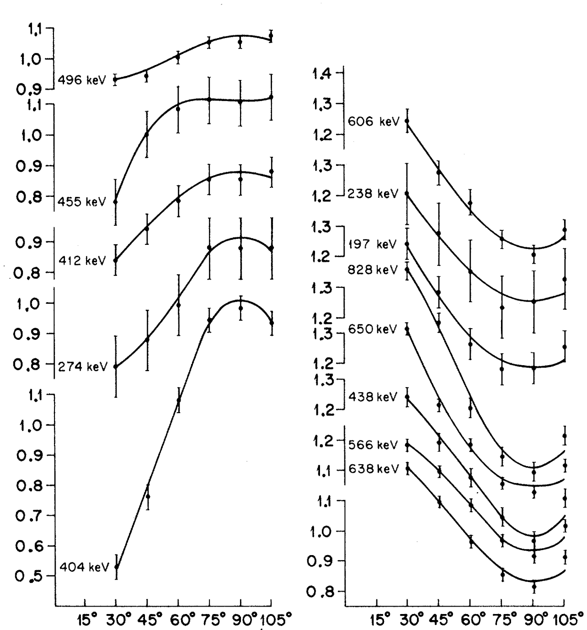

FIG. 6. Angular distributions for γ lines in ^{150}Gd taken at 30-MeV α energies.

keV line. The possibly observed coincidence 650-567 keV is probably due to a somewhat inaccurate background subtraction in our experiment, since the reverse 567-650-keV coincidence is not observed. We have no direct evidence for a 415-keV transition except that the 438-412-keV coincidence is hard to explain without the assumption of a 415-keV transition between the levels at 2117 and 1701 keV. The observed coincidences with the 511-keV photons support the assignment of a 511-keV γ transition to ^{150}Gd by Haenni, Sugihara, and Bowman[9] since we do not expect to observe any β^{+} decay to or from levels in ^{150}Gd.

We follow the suggestion of Haenni, Sugihara, and Bowman[9] for placement of the 511-keV transition in the decay scheme, although the observed 455-511- and 606-511-keV coincidences then once again have to be attributed to inadequate background subtraction of the strong annihilation radiation. Due to the higher background encountered in our in-beam experiment, we fail to observe a few low energy lines of weak intensity, which are placed by Haenni, Sugihara, and Bowman[9] in the decay scheme: notably those of 154.1 keV and the doublet at 180 keV, although we do ob-

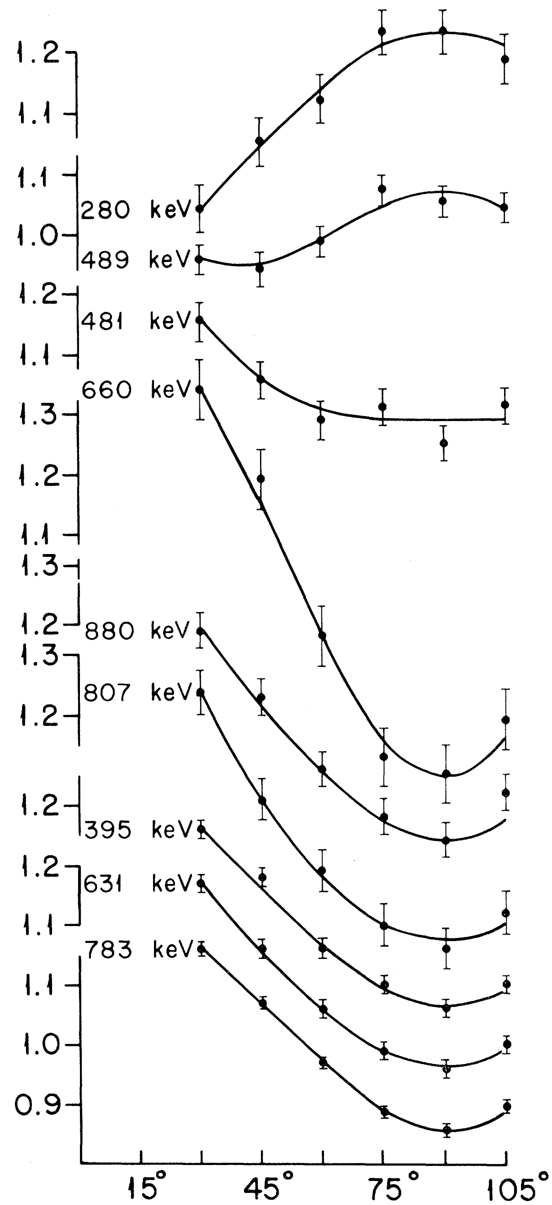

FIG. 7. Angular distributions for γ lines in ^{148}Gd taken at 48-MeV α energies.

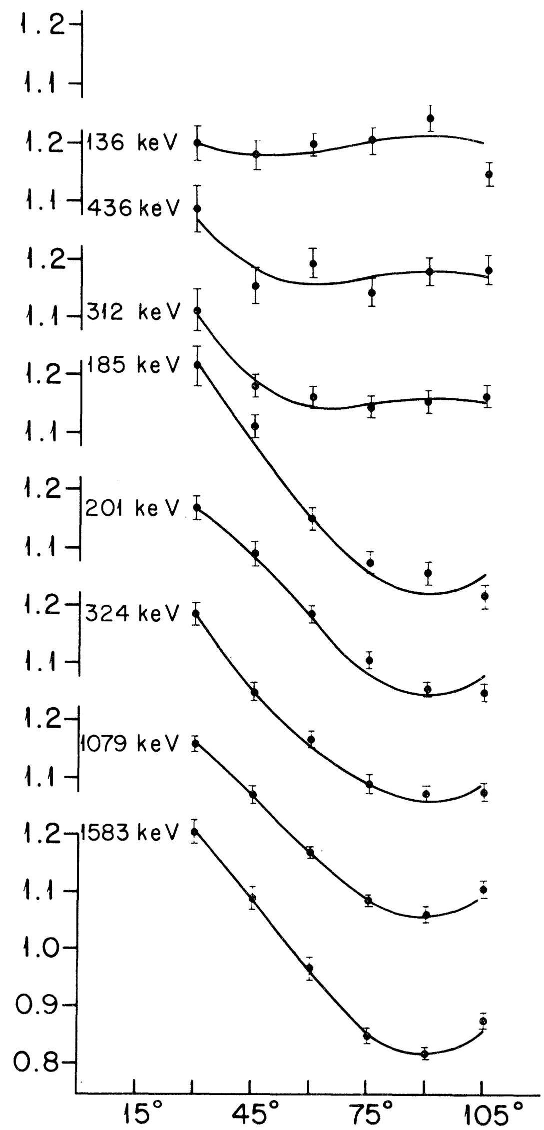

FIG. 8. Angular distributions for γ lines in ^{146}Gd taken at 30-MeV α energies.

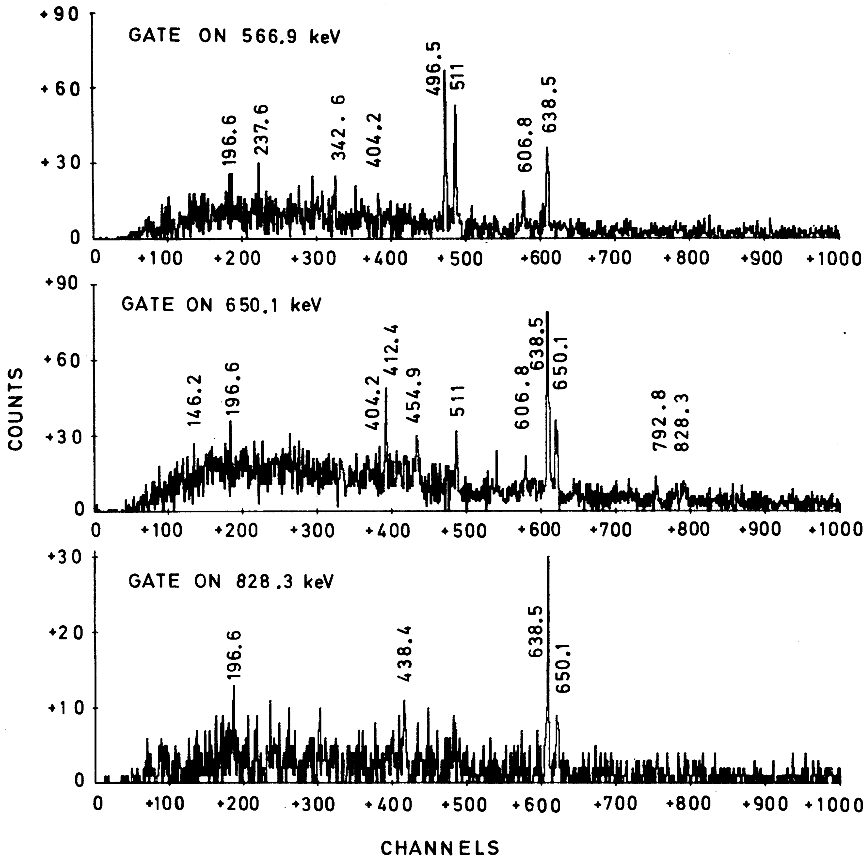

FIG. 9. Coincidence spectra for γ lines in ^{150}Gd taken at 30-MeV α energies.

TABLE IV. Result of coincidence experiment for ^{150}Gd.

Gate	Coincidences Definite	Possible
274	95, 638, 650	
404	146, 412, 511, 606, 650	380, 496
438	412, 567, 638, 650, 828	710
455	182, 511, 638, 650	567
496	146, 342, 511, 567, 606, 638	196, 237, 274, 404
550		182, 496, 511, 606, 638
567	196, 237, 496, 511, 606, 638	342, 404
606	404, 412, 496, 511, 567, 638, 650	
622	412, 496, 511, 567, 638, 650	160, 438, 455, 606, 828, 1017
638	342, 412, 455, 496, 511, 567, 650	95, 404, 550, 606, 828
650	412, 455, 511, 606, 638, 650	146, 196, 404, 567, 792, 828
734		182, 412, 438, 638, 650
828	438, 638, 650	196

serve the higher energy lines that originate from the same levels. For the same reason we believe that we cannot detect the 95.5-keV line observed by Haenni, Sugihara, and Bowman.[9] We therefore place the ~95-keV line which we observe in coincidence with the 274- and 638-keV transitions between the new state we suggest at 2307 keV and the level at 2213 keV. The level at 2307 keV is proposed mainly on the basis of the coincidences with the 606.8-keV line. Further additional levels at 2711, 2857, and 3177 keV are proposed due to the coincidences reported here for the first time involving the 146.2-, 404.2-, and 622.7-keV transitions as well as the energy relationship of the new 550.9- and 1017.2-keV γ transitions. The three γ lines at 183.6, 196.6, and 734.8 keV as well as some very weak lines only observed in the coincidence spectra could not be placed in the decay scheme with any confidence. The 237.6-keV transition, although fairly strong in our singles spectra and also observed by us to be coincident with the 567- and 496-keV transitions, was not reported by Haenni, Sugihara, and Bowman.[9] Within our energy accuracy it could be placed between the two levels at 1701 and 1939 keV. Adopting the more accurate energies of Haenni, Sugihara, and Bowman,[9] a placement of the 237.6-keV transition would result in a discrepancy of 2 keV. Furthermore the angular distribution of the 237.6-keV transition can hardly be reconciled with the spin assigned for these levels (see below). For these three reasons we propose the existence of a doublet of states at 1939 keV, one being depopulated by the 650-keV transitions, the other by the 237.6-keV transition.

The spins of levels in ^{150}Gd have been deduced mainly from our angular-distribution experiment. It was assumed throughout that only $E1$, $M1$, $E2$, and $E2/M1$ transitions are observed. In (α, xn) experiments one usually expects states observed at high excitation energies to have high total angular momentum. All previous investigations[7-9] assign spins of 2^+ and 4^+ to the levels at 638 and 1288 keV, respectively, in agreement with our angular-distribution data. From the angular distributions of the 828.3- and 438.4-keV γ lines

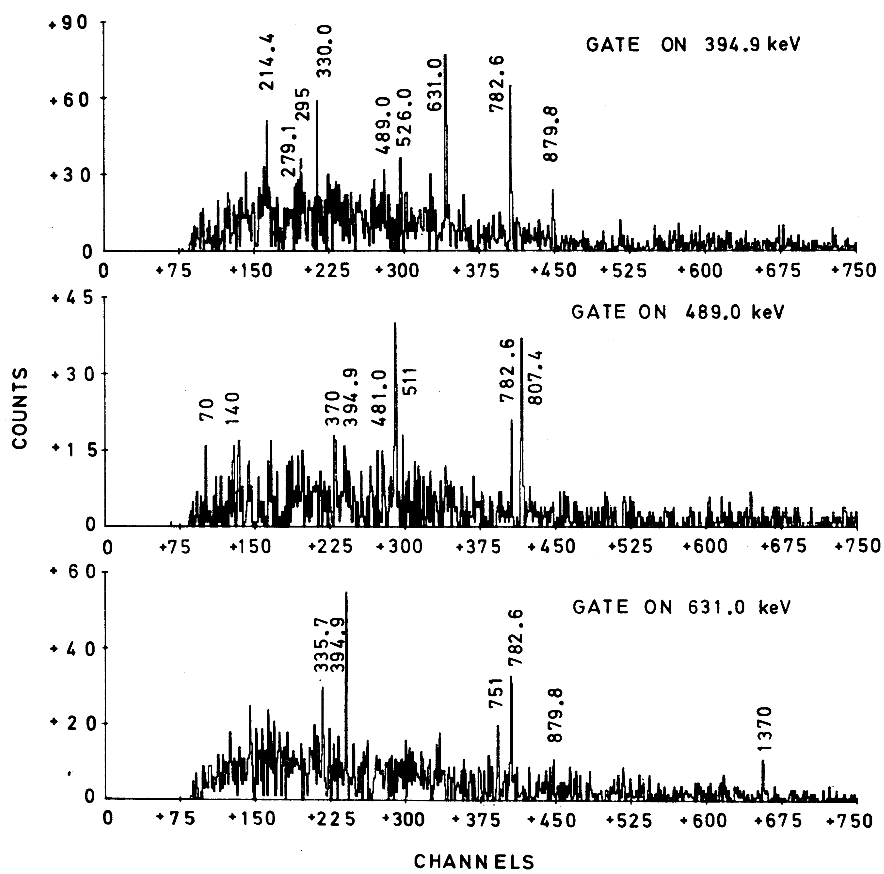

FIG. 10. Coincidence spectra for γ lines in ^{148}Gd taken at 48-MeV α energies.

TABLE V. Result of coincidence experiment for ^{148}Gd.

Gate	Coincidences Definite	Possible
395	330, 631, 783, 880	214, 280, 295, 489, 525
481	489, 511, 783, 807	~455,
489	511, 783, 807	~70, ~140, ~370, 395, 481
631	395, 751, 783	336, 880, ~1370
660	783	~455
751	783	~455, 526
783	395, 631, 660	481, 489, 751
807	783, 489	214, ~224, ~370, ~455, 481
880	395, 631	~198, 526, 783
1010		~198, 214, 280, 336

we infer, under the above assumptions, spins of 6^+ and 8^+ for the levels at 2117 and 2554 keV, respectively. The cascade of transitions 342.6 (dipole), 511, and 566.9 keV then restricts the spin of the 1135-keV level to 3 allowing the maximum (quadrupole) spin change for the subsequent two transitions. This indicates that the 496.5-keV transition has $E1$ character as determined by Kewley *et al.*[7] rather than $E0/M1/E2$ character as proposed by Gono, Araki, and Hiruta.[8] The $E1$ character of the 496.5- and $E2$ character of the 566.9-keV transitions then determine the spins and parities of the 1135- and 1701-keV states to be 3^- and 5^-, respectively. The 511-keV transition and the triple cascade of the two dipole 342.6- and 274.5-keV transitions and the 650-keV transition restrict the spins and parities of the levels at 1939 and 2213 keV to 6^+ and 7^-. This implies that both 650-keV transitions are $E2$ in agreement with the experiment, since otherwise large deviations from the observed angular-correlation pattern would be expected. If the 237.6-keV transition connected the 6^+ 1939-keV state with the 5^- 1701-keV state it should be an $E1$ transition. Only an uncommonly large $M2$ admixture could result in an agreement with our angular-distribution experiment. The spin of the 2307-keV level has been determined to be 5^- from the 95- and 1017-keV lines and the angular distribution of the 606.8-keV transition. The 160-keV transition from the 2554-keV 8^+ level and the angular distribution of the 454.9-keV transition restrict the spins and parities of 2394-keV level to (6^+, $7^\pm$). The large negative A_2/A_0 coefficient of the 404.2-keV transition indicates spin (4^-, 6^-) for the 2711-keV level.

It should be noted that our spin-parity assignments are in agreement with the tentative assignments by Haenni, Sugihara, and Bowman,[9] in particular the 8^+ assignment of the 2554-keV state which was based on the $\log ft$ value of the electron-capture decay from ^{150m}Tb. Our assignments are also in agreement with the multipolarities known for some of the transitions from conversion-electron data.[7] In the assignment of 2^+ to the 1429-keV level we adopt the value of Refs. 7 and 10.

B. ^{148}Gd

The placement of the seven strongest transitions between the levels at 783, 1272, 1414, 1753, 2560, and 2689 keV is quite straightforward from their energy and intensity as well as their coin-

TABLE VI. Result of coincidence experiment for ^{146}Gd.

Gate	Coincidences Definite	Possible
111	136, 201, 1079, 1583	111, 324
136	111, 201, 312, 324, 436, 1079, 1583	
201	111, 136, 324, 436, 540[a], 690[a], 1079, 1583	
312	136, 324, 436, 1079, 1583	
324	111, 136, 201, 312, 436, 1079, 1583	185
436	111, 136, 201, 312, 324, 1079, 1583	
1079	136, 201, 312, 324, 436, 1583	111, 441
1583	136, 201, 312, 324, 436, 1079	111

[a] True coincidences due to contaminant.

cidence relationships. The placement of a ~140-keV transition between the levels at 1414 and 1272 keV is indicated by the 395-489-keV coincidences. From energy considerations we propose a level of 2088 keV being depopulated by the 279.2- and 335.7-keV transitions. This assignment is also in agreement with the 395-280-keV coincidences. The coincidences 1010–280 and 1010–335.7 suggest a level at 3099 keV. However, since the 1010-keV transition is also observed in the decay of ^{148}Tb while the 280-keV transition is not, we are in doubt about the assignment of the 1010-keV line. The strong 660-783-keV coincidences suggest a level at 1443 keV.

The 309.0-keV transition energetically could lead from the 1753-keV state to the 1443-keV level. However, this would be in discrepancy with our observation (Sec. II) that the 481.0-keV transition is delayed with respect to the beam burst while the 309.0-keV line is not. The 395–526 and 880–526 coincidences led us to propose the level at 3215 keV; from the coincidence with the 455-keV transition we suggest a level at 3019 keV. The energy relation of the ~198- and 330.0-keV lines supports this assignment. We suggest a state at 2782 keV in order to place the ~224- and ~1370-keV transitions, which have been observed in our coincidence experiment only. For the remaining weak lines, insufficient information prevented a reliable assignment.

Since the 526.0-keV γ rays are prompt with the beam burst while the 879.8-keV γ rays are delayed, we assign the (17.3 ± 2.0)-nsec isomer to the 2689-keV level. Isomeric transitions in ^{148}Gd have been reported[11] in agreement with our value, but no definite assignment was made. In order to explain that the 481.0- and 489.0-keV transitions are delayed relative to the beam burst, we have to postulate an unobserved transition of either 56 keV from the 1809- to the 1753-keV states or of 129 keV from the 2689- to the 2560-keV levels. In the latter case the 807 transition, for which we cannot make a definite determination due to a possible background line (see Sec. II), would also be delayed relative to the beam bursts. Since the 660.6-, 279-, and 335.6-keV γ rays are prompt with the beam bursts, the main feeding to the levels at 1443 and 2088 keV can only be direct or by γ transitions that bypass the states at 1753, 1809, 2689, and possibly 2560 keV. These might be high energy transitions which would escape detection.

In the assignment of spins and parities to levels up to the state at 2088 keV in excitation we were

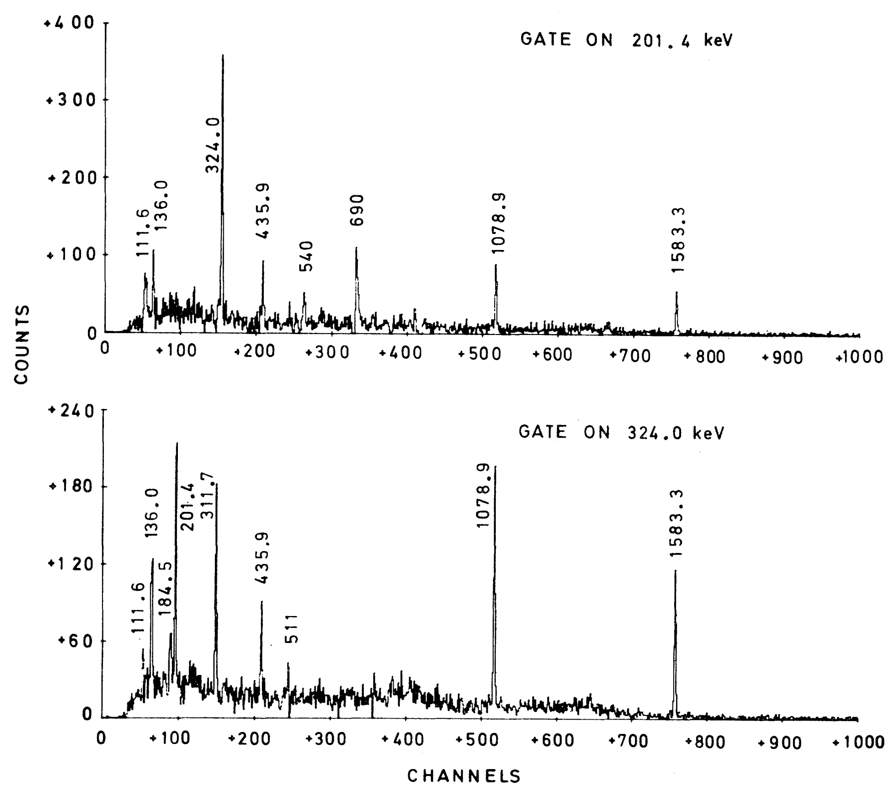

FIG. 11. Coincidence spectra for γ lines in ^{146}Gd taken at 30-MeV α energies.

guided by the similarities of the level sequence of ^{148}Gd with ^{150}Gd as well as ^{148}Sm. These assignments are in agreement with our angular-distribution data. They are not completely compelling but are strongly indicated. In the case of the 1272-keV level, the dipole character of the 489.0-keV transition limits the possible spin values to 1, 2, and 3. The absence of a ground-state transition favors the choice of 3. For the state at 1443 we propose spin 4^+ although again 2^+ would be compatible with the angular distribution of the 660.6-keV γ transition, but in the latter case one would expect population of this level from the ^{148}Tb decay as well as a transition to the ground state. The possible spin and parities for the level at 2560 keV are derived from the ~751-keV transition to the 6^+ 1809-keV state and the angular-distribution data for the 807.4-keV γ line. For the level at 2689 keV a spin-parity of 8^+ has been proposed by Sugihara, Bowman, and Haenni[4] on the basis of γ spectroscopy of the ^{148}Tb decay. This assignment is in agreement with our data especially for the angular distribution of the 879.8-keV line. Although different values, e.g. 6^+ or 7^+, would also be compatible, we adopt the 8^+ value.

C. ^{146}Gd

For ^{146}Gd we only observe seven strong γ transitions which have been reported previously.[6,10] Our data, particularly from the coincidence experiment, clearly favor the placement of the γ transitions between the higher excited states by Kownacki *et al.*[10] over that by Spoelstra.[6] We cannot decide the order of the 111.6- and 201.4-keV transitions, since we have no estimate for the intensity of the 111.6-keV transition in ^{146}Gd due to a masking γ line attributed to ^{147}Gd. We adopt the order proposed in Ref. 10.

Our decay curves for γ lines in ^{146}Gd (Fig. 13) indicate that only the 324.0-, 1078.9-, and 1583-keV transitions decay with the same half-life of $T_{1/2} = 9.1 \pm 2.0$ nsec. The 311.7-keV line clearly decays faster with perhaps a longer lived component. We therefore assign the 9.1 ± 2.0-nsec lifetime to the 2986-keV level. The assignment and value of this lifetime are in agreement with the earlier[10] report of a 13.5 ± 3.5-nsec half-life in ^{146}Gd.

However, there are indications that the decay curves particularly for the 324.0- and 311.7-keV lines do not follow a simple exponential. Our delayed coincidence spectra in Fig. 14 demonstrate that the 3298-keV level is also isomeric. The results of the delayed coincidence experiment (Table VII) and the possible self-coincidences

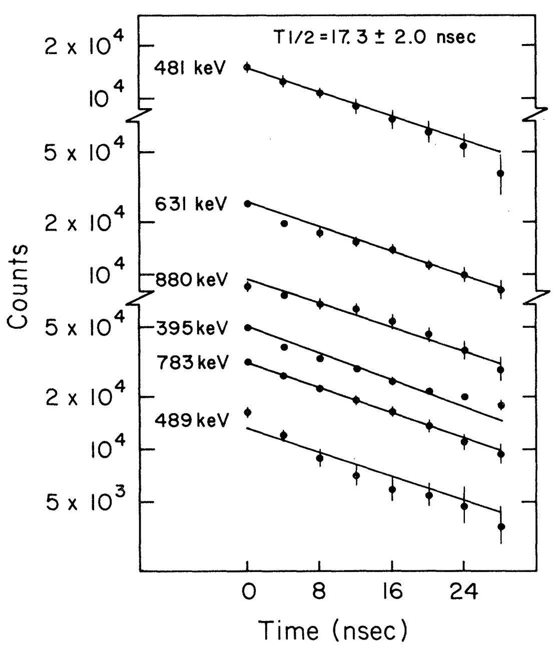

FIG. 12. Decay curves for γ lines from ^{148}Sm(48-MeV $\alpha, 4n\gamma)^{148}$Gd.

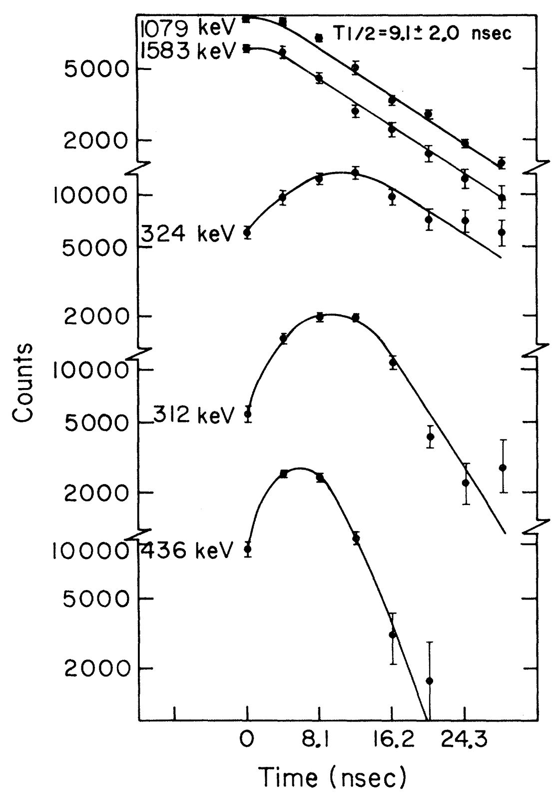

FIG. 13. Decay curves for γ lines from ^{144}Sm(30-MeV $\alpha, 2n\gamma)^{146}$Gd.

TABLE VII. Result of delayed-coincidence experiment for ^{146}Gd.

Gate	Delayed coincidences "γ before"	"γ after"
136		111, 201, 312, 324, 436, 511, 1079, 1583
201	111, 136	324, 1079, 1583
312	136	
324	111, 136, 201	

of the 111.6-keV line lead us to tentatively propose an additional ~435-keV crossover transition from the 3096-keV level to the 2662-keV state and a new state at 3409 keV depopulated by a second ~111-keV transition. These newly assigned γ lines do not contradict the prompt coincidence relationships. From the time range used to obtain the delayed coincidence spectra we infer that the isomer at 3298 keV will have a half-life in the range 10 nsec $\ll T_{1/2}$ (3298 keV) $\lesssim$500 nsec. It seems beyond our capabilities for an exact determination.

Our angular-distribution data are in agreement with the spins proposed[10] for the higher excited states. However we would like to point out that different spin values are also compatible. If one adopts the low-precision conversion-electron data from Ref. 6, of the states we propose only

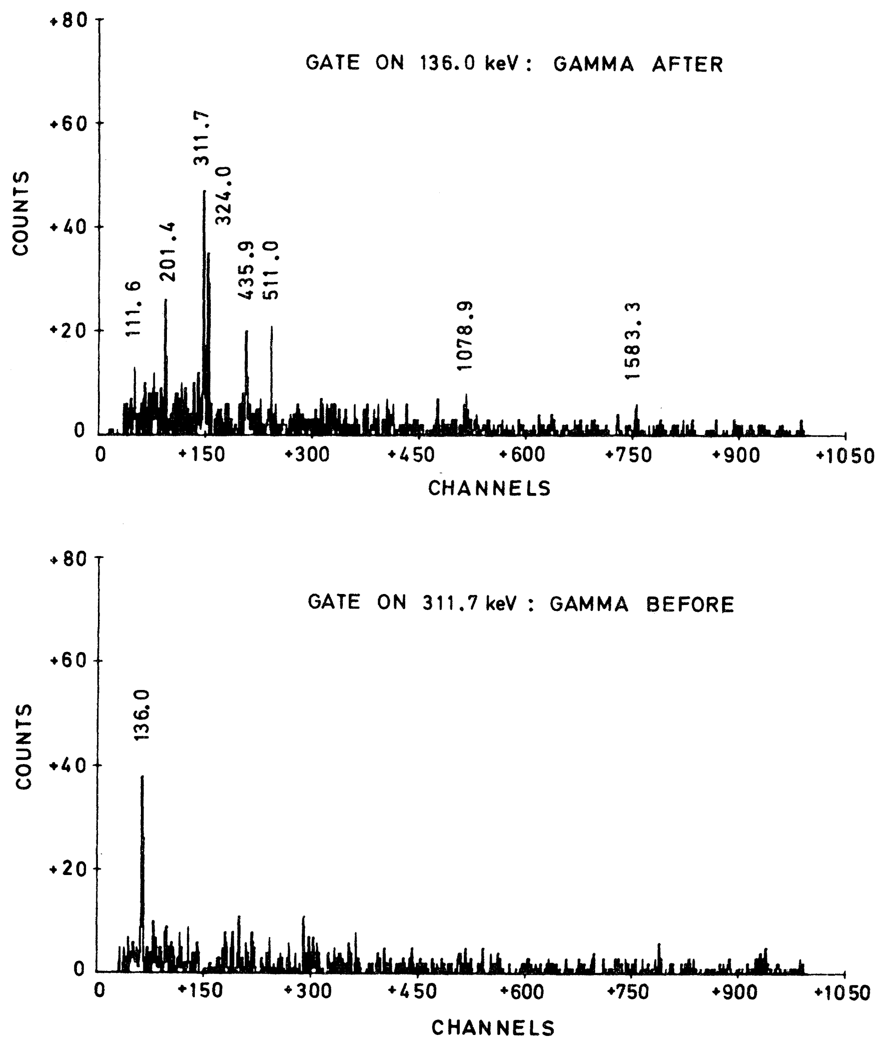

FIG. 14. Delayed coincidence spectra for γ lines in ^{146}Gd taken at 30-MeV α energies.

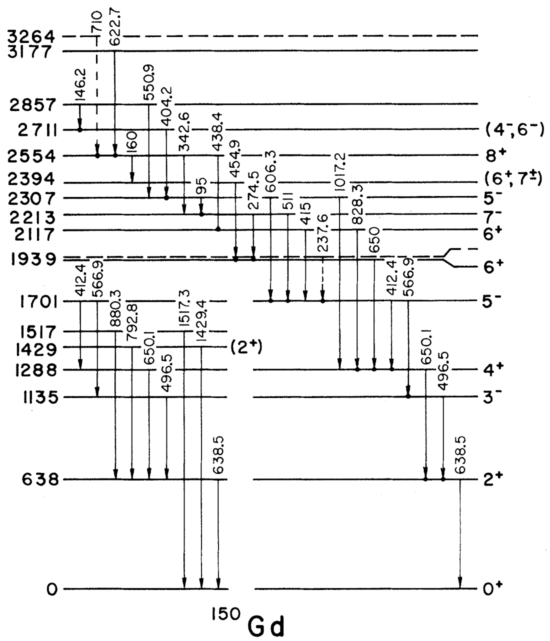

FIG. 15. Decay scheme for ^{150}Gd from in-beam spectroscopy (on right) and from ^{150}Tb decay (on left).

the 3434-keV state is expected to be of negative parity. The 446.0-keV transition proposed in Ref. 10 between this level and the 6^+ 2982-keV state would then have to be an $M2$ transition if the spin sequence proposed in Ref. 10 is to be maintained. Since this 446.0-keV transition is in competition with the 136.0-keV $E1$ transition, we feel uncertain about the spin assignments, multipolarities of the γ rays, and the placement of the weaker γ lines. Further evidence for the newly proposed ~435-keV transition from the 3096-keV level to the 2662-keV state would throw doubts on the previous 8^+ spin assignment of the 3096-keV state made in Ref. 10.

IV. DISCUSSION

In Fig. 18 we display the systematics for the ground-state collective sequence as well as the negative-parity sequence and the second excited 2^+ states known for the Gd isotopes. The 2^+ and 4^+ levels of the ground-state bands extrapolate smoothly and rise in excitation energy. The second 2^+ states which could be interpreted as a vibrational band head in the heavier nuclei exhibit a similar trend. The 6^+ state of ^{148}Gd lying at almost the same excitation energy as the 2^+ second excited state clearly does not follow this pattern. Very similar deviations are found for the even Sm isotones.[13] We tentatively suggest that the first 6^+ and 8^+ levels in ^{148}Gd and ^{150}Gd are perturbed, probably by high-spin two-quasiparticle excitations lying close in energy. For example, two 6^+ states are suggested in ^{150}Gd. Also the long lifetime for the 2689-keV 8^+ state in ^{148}Gd and the 2986-keV 6^+ state in ^{146}Gd are, respectively, hindered by a factor of 6 and 10^3 with respect to the single-particle estimate and therefore are hard to reconcile with their assignment as pure members of a collective sequence based on the ground state. In ^{146}Gd with a closed neutron shell, the first excited 4^+ and 6^+ states

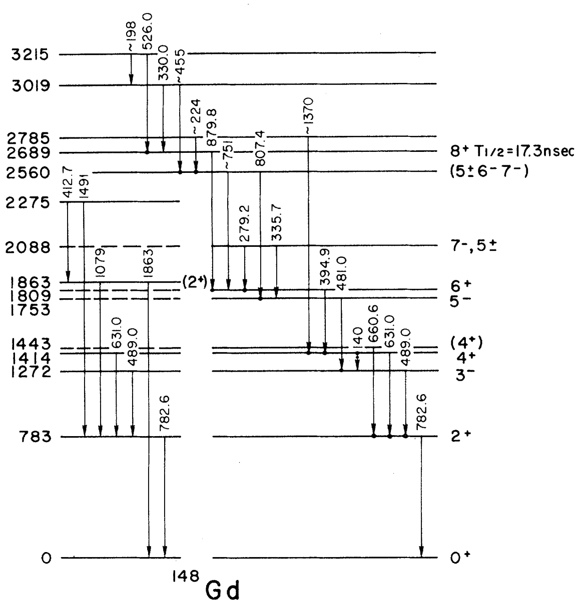

FIG. 16. Decay scheme for ^{148}Gd from in-beam spectroscopy (on right) and from ^{148}Tb decay (on left).

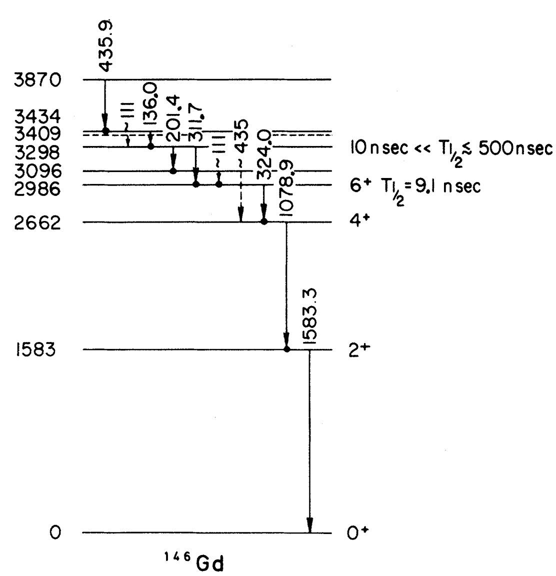

FIG. 17. Decay scheme for ^{146}Gd from in-beam spectroscopy.

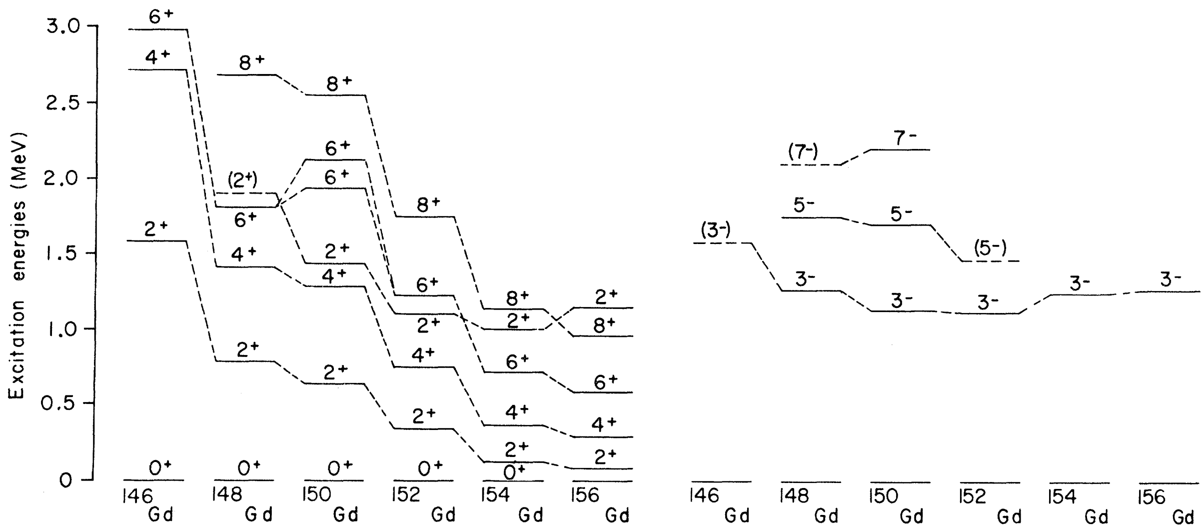

FIG. 18. Systematics of states in even Gd isotopes.

have been interpreted[10] as mainly due to $\pi(g_{7/2})^2$ configuration although Heyde, Waroquier, and Vanden Berghe[14] predict admixtures of $\pi(d_{5/2}, g_{7/2})$. Our somewhat lower value for the half-life of this state may favor the pure $\pi(g_{7/2})^2$ configuration.

In the light Gd isotopes excluding the closed-shell ^{146}Gd, the neutron configurations additionally should also be taken into account. The 2554-keV 8^+ state in ^{150}Gd has been interpreted[9] as $\nu(h_{9/2}, f_{7/2})_{8^+}$ configuration. This level and the corresponding 8^+ state in ^{148}Gd at 2698 keV are both populated by β decay with comparable logft values ~4.5 from presumably[4, 10] 9^+ isomeric levels in ^{148}Tb and ^{150}Tb, respectively. $\frac{7}{2}^-$ and $\frac{9}{2}^-$ spins and parities are assigned[15] for the ground states and low excited states in ^{147}Gd, ^{149}Gd, and ^{145}Sm, which indicates that the configuration $\nu(h_{9/2}, f_{7/2})$ can be expected as a low-lying two-quasiparticle state in the light Gd isotopes with presumably additional configuration admixtures.

We suggest from Fig. 18 that the 8^+ state in ^{150}Gd is still rising smoothly with decreasing neutron number and may still have collective character. In ^{148}Gd the 8^+ 2689-keV state decays predominantly to the 1863-keV 6^+ state. The measured lifetime furnishes further information of the possible configuration of this state. In Table VIII we list theoretical $B(E2\downarrow)$ values for some possible quasiparticle configurations including a possible proton configuration. These values have been calculated as outlined in Ref. 16. The $\langle r^2 \rangle$ matrix elements have been estimated using the formulas (11a) and (11b) of Ref. 17. Comparison of these values with the experiment $B_{\exp}(E2, 8^+ \rightarrow 6^+) = 0.062\ e^2\,\mathrm{fm}^4$ suggests components of the $\nu(h_{9/2}, f_{7/2})_{8^+}$ and $\nu(h_{9/2}{}^2)_{6^+}$ configurations in the 8^+ 2689- and 6^+ 1863-keV states, respectively. A value $e_{\text{eff}} = 0.6e$ would yield close agreement.

The 3^- states in the light Gd isotopes could be explained either as two-quasiparticle configurations or as collective states. Probably both are present. For example low-lying $\frac{11}{2}^-$ proton states are known[18] in the more spherical odd-A isotopes ^{147}Gd–^{151}Gd.

A striking feature of the negative-parity states is the apparent sequence $3^-, 5^-, 7^-$ suggested for both ^{148}Gd and ^{150}Gd. In this context it may be mentioned that similar regular sequences includ-

TABLE VIII. Theoretical $B(E2)$ values for nucleon configurations in ^{148}Gd.

Configuration Initial	Configuration Final	$B(E2)$ ($e^2\,\mathrm{fm}^4$)
$\nu(h_{9/2}, f_{7/2})_{8^+}$	$\nu(h_{9/2}, f_{7/2})_{6^+}$	14.2
$\nu(h_{9/2}, f_{7/2})_{8^+}$	$\nu(h_{9/2}{}^2)_{6^+}$	0.25
$\nu(h_{9/2}, f_{7/2})_{8^+}$	$\nu(f_{7/2}{}^2)_{6^+}$	0.82
$\nu(h_{9/2}{}^2)_{8^+}$	$\nu(h_{9/2}, f_{7/2})_{6^+}$	1.49
$\nu(h_{9/2}{}^2)_{8^+}$	$\nu(h_{9/2}{}^2)_{6^+}$	30.5
$\pi(h_{11/2}{}^2)_{8^+}$	$\pi(h_{11/2}{}^2)_{6^+}$	59.6

TABLE IX. $B(E1)/B(E2)$ transition probabilities for ^{150}Gd.

$$\frac{B(E1;\ 4^+ \rightarrow 3^-)}{B(E2;\ 4^+ \rightarrow 2^+)} = 4.55 \times 10^5$$

$$\frac{B(E1;\ 5^- \rightarrow 4^+)}{B(E2;\ 5^- \rightarrow 3^-)} = 3.64 \times 10^5$$

$$\frac{B(E1;\ 6^+ \rightarrow 5^-)}{B(E2;\ 6^+ \rightarrow 4^+)} = 5.27 \times 10^5$$

$$\frac{B(E1;\ 8^+ \rightarrow 7^-)}{B(E2;\ 8^+ \rightarrow 6^+)} = 2.52 \times 10^5$$

ing the 9^- and sometimes the 11^- members have been suggested for ^{146}Sm (Ref. 13) as well as other transitional nuclei (e.g. Refs. 16, 19–21). Enhanced $B(E2)$ transitions between these states[16, 21] are also reported. Elbek *et al.*[22] using deuteron inelastic scattering has estimated that the $B(E3)$ values connecting the 0^+ ground states with these 3^- states vary from 7.6 to 33 single-particle units for ^{160}Gd to ^{152}Gd and concludes they have considerable collective character. Examining the data for the Sm isotones of ^{148}Gd and ^{150}Gd we may infer this collectivity increases for these lighter species. The sequence of negative-parity states could then be interpreted as a collective sequence based on the 3^- state. With such an interpretation there remains the problem of the apparent occurrence of only odd-spin states. This of course would be expected in a deformed nucleus for a $K = 0^-$ sequence, however no 1^- state expected for such a sequence has apparently been found. Alternatively one could suggest a special stretch coupling of the 3^- state and the angular momentum carried by a deformed ground-state collective sequence as has been observed in moderately deformed nuclei, e.g., for the light odd-A La isotopes.[23] With this interpretation the $E2$ transition probability between the negative-parity states would be comparable to that of the ground-state band. Additionally the $E1$ transitions connecting the even- and odd-parity bands should have comparable hindrance. This may be tested for the case of states in ^{150}Gd as shown in Table IX where four energy reduced radiative transition probabilities, $\|\Gamma(E1)\|/\|\Gamma(E2)\|$, are compared and found to be constant within a factor of approximately 2 using the accurate intensity data from Ref. 9. This suggests that in ^{150}Gd, at least, the negative-parity members form a sequence of closely related states.

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