Levels in ^{146,147,148}Gd observed following the decay of their terbium parents including a new isotope, ^{146}Tb†

E. Newman, K. S. Toth, and D. C. Hensley
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

W-D. Schmidt-Ott*
UNISOR,‡ Oak Ridge, Tennessee 37830
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The decay schemes of the following terbium isotopes were investigated: 2.3±0.2-min ^{148}Tb, 1.9±0.1-min and 1.6±0.1-h ^{147}Tb, and a previously unreported 23±2-sec nuclide assigned to ^{146}Tb. These radioactivities were produced by bombarding ^{141}Pr with ^{12}C ions accelerated in the Oak Ridge isochronous cyclotron. Both singles and coincidence γ-ray spectral measurements were made. Our data for 2.3-min ^{148}Tb are in excellent agreement with the recently published results of Bowman, Haenni, and Sugihara. We also confirm their discovery of a new 1.9-min high-spin isomer in ^{147}Tb and provide additional information concerning its decay properties. Levels in ^{147}Gd populated by this (presumably $h_{11/2}$) ^{147}Tb state are: 997.6 keV, $\frac{9}{2}^-$; 1397.7 keV, ($\frac{9}{2}^-$); (1778.9 keV); and 1797.8 keV, ($\frac{9}{2}^-$). Contrastingly, the 1.6-h low-spin (probably $d_{5/2}$) ^{147}Tb isomer was found to populate the following ^{147}Gd levels: 0 keV, $\frac{7}{2}^-$; 1152.2 keV, $\frac{3}{2}^-$; 1292.0 keV, ($\frac{3}{2}^+$); 1411.5 keV, ($\frac{1}{2}^+$); 1699.2 keV; 1759.1 keV; and 1846.6 keV, ($\frac{5}{2}^-$). The assignment of the new 23-sec activity to ^{146}Tb is based primarily on the fact that five of its γ-rays have been observed by Kownacki *et al.* in a ^{144}Sm(α, 2$n\gamma$) study. Levels in ^{146}Gd seen in the decay of ^{146}Tb (probable spin of 3) are as follows: 1579.5 keV, 2^+; 2658.4 keV, 4^+; 2982.4 keV, 6^+; 2996.9 keV; 3099.4 keV; (3139.6 keV); and 3313.4 keV. In contrast to the results of Kownacki *et al.* γ rays either feeding or deexciting their tentatively proposed 3^- level at 1584.5 keV were not observed.

RADIOACTIVITY ^{146,147,148}Tb; measured $T_{1/2}$, E_γ, I_γ, $\gamma\gamma$ coin; discovered new isotope ^{146}Tb; ^{146,147,148}Gd deduced levels, J, π. Ge(Li) detectors, 2.1 and 3.0 keV at 1.33 MeV.

I. INTRODUCTION

The study of the systematics of nuclear properties of isotopes with 81, 82, and 83 neutrons is a prerequisite for extending shell-model calculations to this region of the Periodic Table. In particular, the assumption of a doubly magic $N = 82$, $Z = 50$ core for 82-neutron odd-mass nuclei has made possible detailed microscopic calculations[1] of the properties of their levels. Unfortunately, the unavailability of stable targets with $N = 82$ beyond ^{144}Sm essentially rules out the investigation of nuclei with $Z > 63$ by means of direct reactions, and, instead, one must rely on decay-scheme and in-beam γ-ray studies.

The original intent of the present study was to examine levels in ^{147}Gd populated in the decay of ^{147}Tb as a logical continuation of our earlier investigation[2] of levels in its isotone, ^{145}Sm. In that publication,[2] by examining data for even-Z $N = 83$ isotopes, we predicted the approximate excitation energies for several as yet unreported single-neutron states in ^{147}Gd. In-beam data are available[3] for that particular nucleus together with information obtained in ^{147}Tb decay studies.[4,5] Chu, Franz, and Friedlander[4] were the first to report the existence of two isomers in ^{147}Tb, one with a 1.6-h half-life and the other, apparently a high-spin isomer, with a half-life of 2.5 min. A decay-scheme study for the longer-lived isomer was later published by Afanasiev *et al.*[5] We felt that a detailed investigation of the decay properties of the two ^{147}Tb isomers was warranted to supplement the in-beam γ-ray measurements.[3]

Shortly after we began our study, it became apparent that the γ rays reported[4] for the 2.5-min species were in fact associated with a high-spin isomer in ^{148}Tb discovered by Arlt *et al.*[6] A recent study by Bowman, Haenni, and Sugihara[7] confirms this assignment to a high-spin isomer in ^{148}Tb and reports the existence of a 1.83±0.06-min isomeric state in ^{147}Tb. In the meantime, we had also undertaken a search for a possible high-spin isomer in ^{147}Tb and found it to have a 1.9 ±0.1-min half-life. In the course of looking for the short-lived ^{147}Tb activity, we found and investigated the decay of a new 23 ± 2-sec isotope which we identify as ^{146}Tb.

II. EXPERIMENTAL METHOD

The terbium activities were produced by bombarding ^{141}Pr with ^{12}C ions accelerated in the Oak Ridge isochronous cyclotron (ORIC). Two experimental assemblies were used, one for the study of hour-long activities and the other for activities with half-lives in the minute and second range. Both systems use the helium gas-jet technique.[8] The basis for this technique is that recoil product nuclei ejected from thin targets by the incident beam are stopped in helium gas and then swept out together with the gas through an orifice. For the long-lived activities an aluminum catcher foil was placed directly behind the orifice to collect the radioactive products. After a suitable bombardment time the catcher foil was then removed for γ-ray counting in a shielded area while the irradiation and collection cycle was repeated with a new collector foil. To investigate the short-lived isotopes, a Teflon capillary was inserted into the orifice, and the other end of the capillary tube, situated outside the experimental room, was pumped on to extract the product nuclei into the shielded area. Details of this capillary system have been described in a recent publication.[9]

The target consisted of a ~240-μg/cm^2 layer of praseodymium oxide deposited onto a 25-μm beryllium foil which served as the entrance window to the high-pressure chamber where the recoils were stopped in the helium gas. The energy of the ^{12}C beam deflected out of the cyclotron was about 118 MeV, but because the backing foil intercepted the beam first, the maximum incident energy on target was ~110.5 MeV. Additional beryllium-metal foils were used to reduce the beam energy as needed to obtain excitation functions and to emphasize the yield of a particular product.

Singles and coincidence γ-ray spectra were measured with Ge(Li) detectors. The γ-γ coincidence data were digitized with the ORIC analog-to-digital-converter (ADC) system which has approximately a 9000-channel resolution capability. The ADC system is a fast on-line system interfaced to an in-house computer and the coincidence data were stored in a list mode on a disc with a million-word capacity. Singles spectra were taken at the same time with a 4096-channel analyzer which is also interfaced with the computer. For permanent storage and later data reduction, all information was transferred onto magnetic tapes. The coincidence data were analyzed by first obtaining "collapsed" spectra from each detector. Windows were then set over prominent peaks, and spectra in coincidence with them were projected out. Computer codes were used to obtain γ-ray peak positions and areas, and to convert these into energies and intensities, respectively.

III. RESULTS AND DISCUSSION

A. Mass assignments

Before discussing the various decay schemes, we would like to examine the information on which the nuclidic mass assignments are based. First, the assignment of the new 23-sec activity to ^{146}Tb is based principally on the fact that its two most intense γ rays have been observed in a ^{144}Sm(α, 2n) in-beam study[10] and correspond to the cascade $4^+ \to 2^+$ (first excited state) $\to 0^+$ (ground state) in ^{146}Gd. Second, the assignment of the 2.3-min activity to ^{148}Tb is now certain, since several of its γ rays have been observed[11] in the decay of the 66-min low-spin isomer of ^{148}Tb by a group at Dubna that utilized a mass-separated source. Third, mass separation was also used by Afanasiev *et al.*[5] to establish the mass of the 1.6-h ^{147}Tb activity. Curiously, however, the two strongest γ rays that follow the decay of the 1.9-min activity are seen in neither the 1.6-h ^{147}Tb decay nor in the in-beam work.[3] This fact was also noted by Bowman, Haenni, and Sugihara.[7] In contrast to their results, however, we were able to observe a weak γ ray with a 1.9-min half-life that corresponds to the most intense transition seen in the in-beam γ-ray study.[3]

Primarily because of the uncertainty in the assignment of the 1.9-min activity, we measured yields as a function of the ^{12}C energy for strong transitions in the decay of the 2.3-min, 1.9-min, and 23-sec radioactivities. These yield curves are shown in Fig. 1. The 784.5-keV γ ray represents essentially all of the decay strength of 2.3-min ^{148}Tb, the 1397.7- and 1797.8-keV γ rays are by far the most intense 1.9-min transitions, and the 1579.5-keV γ ray, as discussed later, encompasses most of the decay strength of the 23-sec ^{146}Tb. The yields were corrected for differences in beam intensities and half-lives but are expressed in relative units because the efficiency of the gas-jet-capillary system is not known precisely. It is seen that the 2.3-min ^{148}Tb has a maximum yield at ~82 MeV while the 1.9-min activity peaks at ~102 MeV; this is good evidence in support of assigning this latter activity to ^{147}Tb. While the yield for the 23-sec activity has not reached a maximum in the energy range investigated, the data are consistent with it being the

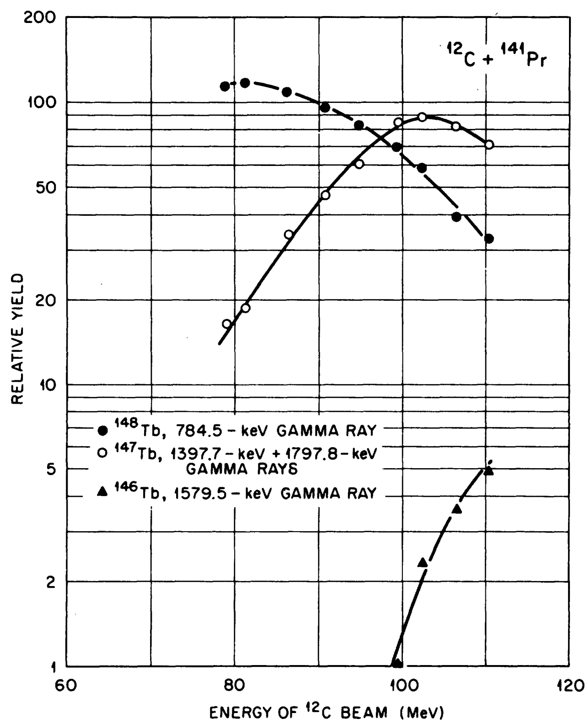

FIG. 1. Relative yields measured as a function of bombarding energy for intense γ rays that follow the decay of 2.3-min ^{148}Tb, 1.9-min ^{147}Tb, and 23-sec ^{146}Tb.

^{141}Pr(^{12}C, 7n) product. Note that its yield relative to those of ^{148}Tb and ^{147}Tb is low. The two latter activities are high-spin isomers and should be enhanced in heavy-ion-induced reactions relative to their corresponding low-spin isomers. One might speculate, then, that the 23-sec activity represents a low-spin isomer and that a high-spin isomer, as yet undiscovered, exists in ^{146}Tb. If this is true, then the half-life of such a high-spin isomer would probably be less than about one second because counting was not started until a few seconds after the helium flow had been interrupted, to allow for a complete sweep out of the gas in the capillary.

B. Levels in ^{148}Gd

Our results for the decay of 2.3-min ^{148}Tb are in agreement with those published in Ref. 7, that is, (1) the same number of γ rays were assigned to its decay, (2) transition energies and photon intensities measured in the two investigations agree within error limits, and (3) the two decay schemes, deduced from all available evidence, are identical. Figure 2 shows this level scheme. We have included in Fig. 2 a partial decay scheme for the low-spin 66-min ^{148}Tb isomer. These data were obtained during our measurements for the 1.6-h ^{147}Tb activity, and the bombarding energy, consequently, was not optimized for the $A = 148$

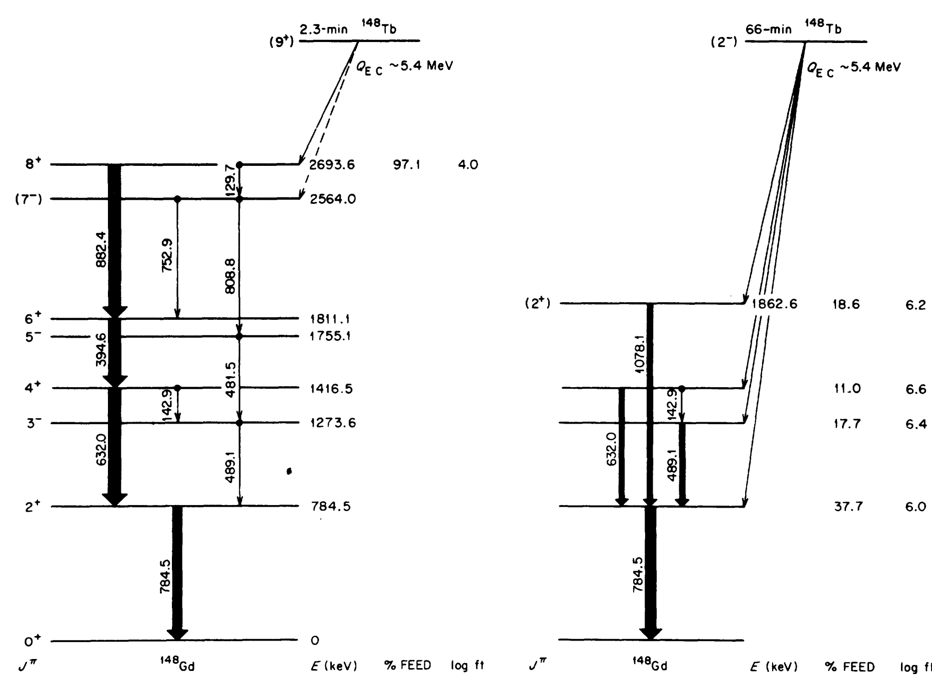

FIG. 2. Decay schemes for 2.3- and 66-min ^{148}Tb. See the text concerning the proposed (taken from Ref. 11) 2$^-$ assignment for the longer-lived isomer.

species. Therefore, only the strongly populated levels in ^{148}Gd could be established from the coincidence measurements. The partial scheme, however, agrees with the more complete results of Vylov *et al.*[11]

As seen in Fig. 2, the 2.3-min ^{148}Tb decays almost entirely to the 2693.6-keV level in ^{148}Gd. The main deexcitation takes place via the following cascade: 882.4 → 394.6 → 632.0 → 784.5 keV. The specific sequence is established not from coincidence information alone, but from in-beam γ-ray studies (see, e.g., Ref. 12) where the intensities of the four γ rays are sufficiently different so that the order of deexcitation can be determined. The level at 1273.6 keV and, therefore, the placement of the 142.9- and 489.1-keV transitions is established from the decay of the 66-min isomer (our data and those of Ref. 11). The placement of the four remaining transitions assigned to 2.3-min ^{148}Tb is not as certain and thus deserves more discussion.

Bowman, Haenni, and Sugihara[7] set gates on only the four strong transitions, i.e., 394.6, 632.0, 748.5, and 882.4 keV. We were able to extract additional coincidence information by setting gates on the 129.1-, 142.9-, 481.5-, 489.1-, and 808.8-keV transitions. The data from these five gates are summarized in Table I where coincidences with the 10 transitions assigned to 2.3-min ^{148}Tb are indicated. Energies and intensities for the 10 γ rays also appear in Table I. The results in Table I show that the 129.7-, 481.5-, and 808.8-keV γ rays are in coincidence with one another and also with the 489.1-keV γ ray; they are not coincident with the 142.9-keV transition. The data, however, do not tell us the cascade sequence of the 129.7-, 481.5-, and 808.8-keV transitions. In Ref. 7 the sequence order was based mainly on the fact that a level at 1755 keV had been reported

TABLE I. Summary of transition and coincidence data for 2.3-min ^{148}Tb.

Observed transitions		Gating transitions (keV)				
E_γ (keV)	I_γ	129.7	142.9	481.5	489.1	808.8
129.7 ± 0.2	2.7 ± 0.3			×	×	×
142.9 ± 0.2	2.1 ± 0.2				×	
394.6 ± 0.1	90.0 ± 5.0		×		×	
481.5 ± 0.2	2.6 ± 0.3	×			×	×
489.1 ± 0.2	5.2 ± 0.5	×	×	×		×
632.0 ± 0.1	90.0 ± 5.0					
752.9 ± 0.3	2.0 ± 0.2	×	?			
784.5 ± 0.1	100[a]	×	×	×	×	×
808.8 ± 0.3	2.7 ± 0.3	×		×	×	
882.4 ± 0.1	94.4 ± 5.0		×		×	

[a] Intensities are normalized to a value of 100 for the 784.5-keV transition.

in an in-beam γ-ray study.[13] The more recent in-beam investigation[12] also proposes a level at 1753 keV and another one at 2560 keV. In this latter in-beam study the 481.5- and 808.8-keV γ rays were found to have equal intensities, but the 129.7-keV γ ray was not observed. The evidence, then, indicates that the 129.7-keV transition belongs at the top of the cascade and that there is a state at 2564.0 keV. The data in Table I indicate that the 752.9-keV transition is in coincidence with the 129.7-keV γ ray, but not with 481.5-, 489.1-, and 808.8-keV transitions. In addition its energy fits well between the levels at 2564.0 and 1811.1 keV, thus supplying further support for the existence of the 2564.0-keV state. Similar arguments, however, cannot be mustered for the intermediate state to be at 1755.1 and not 2082.4 keV. Both in-beam studies[12,13] report a state at ~2092 keV, with a 335-keV transition proceeding from it to a state of ~1755 keV. The level scheme shown in Fig. 2, therefore, goes along with this evidence and places the intermediate state at 1755.1 keV.

Spin assignments shown in Fig. 2 are taken from previous investigations.[6,7,11-13] In Ref. 12 the 2564.0-keV level was assigned possible spins of 5^-, 6^-, and 7^-. If the decay scheme shown in Fig. 2 is correct, then it would appear that this level is populated directly. The spin of 2.3-min ^{148}Tb has been suggested[7,14] to be 9^+ (a result of coupling an $h_{11/2}$ proton to an $f_{7/2}$ neutron). In that event, only a 7^- assignment is reasonable for the 2564.0-keV state. Arlt *et al.*[14] examined the properties of nuclei in this region and concluded that their levels could be understood in terms of two-particle excitations. They propose that the 0^+, 2^+, 4^+, and 6^+ levels in ^{148}Gd are the result of coupling two $f_{7/2}$ neutrons while the 8^+ level at 2693.6 keV results from coupling one $f_{7/2}$ and one $h_{9/2}$ neutron. At that time the 5^- and (7^-) states (see Fig. 2) had not been reported. Arlt *et al.*,[14] however, proposed that 5^-, 7^-, and 9^- states in the neighboring nuclei, ^{148}Sm and ^{150}Gd, represented bands built up on the lowest 3^- states. They also noted that in ^{148}Sm the level spacing was typical of a quasirotational band, i.e., the energy interval between the levels increased with increasing spin. This also seems to be true for the 3^-, 5^-, and (7^-) states in ^{148}Gd. By assuming a ^{148}Tb electron-capture-decay energy of 5.4 MeV[15,16] and a 97% decay branch, a logft value of ~4.0 can be calculated for populating the 2693.6-keV state. This value is consistent with what one would expect for the allowed transition $9^+ \rightarrow 8^+$.

For the 66-min ^{148}Tb decay, logft values indicated in Fig. 2 are based on the assumption that the 784.5-keV transition represents 100% of all

TABLE II. Summary of transition and coincidence data for 66-min ^{148}Tb.

Observed transitions		Gating transitions (keV)			
E_γ (keV)	I_γ	489.1	632.0	784.5	1078.1
142.9 ± 0.2	~0.3	×		×	
489.1 ± 0.2	22.2 ± 2.5			×	
632.0 ± 0.1	15.1 ± 2.0			×	
784.5 ± 0.1	100 [a]	×	×		×
1078.1 ± 0.2	12.1 ± 1.5			×	

[a] Intensities are normalized to a value of 100 for the 784.5-keV transition.

decays, thus neglecting any direct feeding of the ^{148}Gd ground state. (The transition and coincidence data for the 66-min ^{148}Tb are summarized in Table II.) Population by transitions from higher states was taken into account by using the data of Vylov *et al.*[11] In that work the authors assumed the spin of 66-min ^{148}Tb to be 2^-. The log*ft* value for the 4^+ state at 1416.5 keV, however, is much too small for a first-forbidden unique transition. The evidence thus indicates that the spin of 66-min ^{148}Tb is probably 3. The log*ft* calculations were made by assuming only electron-capture decay because the positron intensity[11] is only 22% relative to that of the 784.5-keV transition. Inclusion of any positron contribution would only slightly increase the log*ft* values shown in Fig. 2. Incidentally, in the case of the 2.3-min ^{148}Tb activity, it makes little difference whether only positron or only electron-capture decay is assumed.

C. Levels in ^{147}Gd

The two isomers in ^{147}Tb almost certainly are due to the odd 65th proton being in either the $d_{5/2}$ or $h_{11/2}$ orbital. In a study[17] of levels in ^{145}Eu, the systematics of single-proton centroids in odd-mass $N=82$ isotones was examined. For ^{145}Eu the first three states are as follows: 0 keV ($d_{5/2}$), 330 keV ($g_{7/2}$), and 716 keV ($h_{11/2}$). The indication, however, was that with increasing Z the $h_{11/2}$ orbital was dropping rapidly in excitation energy while the $g_{7/2}$ orbital was rising. The possibility that in ^{147}Tb these orbitals would cross, giving rise to an $E3$ isomer is now confirmed by the fact that a 1.9-min high-spin isomer has been found.

Let us consider first the decay scheme of 1.6-h ^{147}Tb (presumably the $d_{5/2}$ ground state). In Table III we compare our γ-ray energies and intensities with those reported in Refs. 4 and 5. Our intensities are based on an absolute value of 31.3% for the 694.4-keV transition. This number is an average of the absolute intensities reported in Refs. 4 and 5 for the same transition. Chu, Franz, and Friedlander[4] assigned only 3 γ rays to ^{147}Tb decay, while Afanasiev *et al.*[5] reported 15 transitions. Of these we did not observe two, i.e., the 936.0- and 1660-keV transitions. We did see, however, a new γ ray with an energy of 434.8 keV. Gates were set on the 119.7-, 139.8-, 554.7-, 694.4-, and 1152.2-keV γ rays, and the coincidence information is summarized in Table IV.

With the use of these coincidence data a decay scheme was constructed (see Fig. 3). It is es-

TABLE III. Transition energies and photon intensities for 1.6-h ^{147}Tb.

Present data		Reference 5		Reference 4	
E_γ (keV)	I_γ (% of decay)	E_γ (keV)	I_γ (% of decay)	E_γ (keV)	I_γ (% of decay)
119.7 ± 0.4	4.4 ± 0.4	119.7 ± 0.5	6.7 ± 0.7	118.5 ± 0.3	5.1 ± 1.0
139.8 ± 0.4	19.9 ± 2.0	139.8 ± 0.5	33.7 ± 3.4	139.4 ± 0.5	24 ± 3
182.0 ± 0.4 [a]	0.3 ± 0.1	183.5 ± 1.0	0.45 ± 0.11		
347.4 ± 0.6	1.7 ± 0.2	347.4 ± 0.5	2.6 ± 0.4		
407.0 ± 0.4	1.4 ± 0.2	407.4 ± 0.5	1.6 ± 0.3		
434.8 ± 0.6	0.7 ± 0.2				
547.2 ± 0.4	2.0 ± 0.2	547.2 ± 0.5	1.8 ± 0.2		
554.7 ± 0.4	3.7 ± 0.4	554.9 ± 0.5	3.8 ± 0.4		
694.4 ± 0.4	31.3 [b]	694.5 ± 0.5	30.6 ± 3.1	694.4 ± 0.5	32 ± 4
		936.0 ± 0.5	1.7 ± 0.4		
1152.2 ± 0.4	72.5 ± 5.5	1153.0 ± 0.5	75.0 ± 7.6		
1628.1 ± 0.4 [a]	2.7 ± 0.3	1629 ± 1	2.4 ± 0.4		
		1660 ± 1	2.7 ± 0.4		
1948.3 ± 0.4 [a]	1.4 ± 0.2	1949 ± 1	1.5 ± 0.4		
2561.9 ± 0.4 [a]	1.7 ± 0.2	2564 ± 1	1.7 ± 0.6		
2681.4 ± 0.4 [a]	2.6 ± 0.3	2684 ± 1	3.4 ± 0.7		

[a] Transitions not included in the decay scheme shown in Fig. 3.

[b] Intensities for the present data are based on a value of 31.3% for the 694.4-keV transition. This value is an average of the two intensities for the same transition as reported in Refs. 4 and 5.

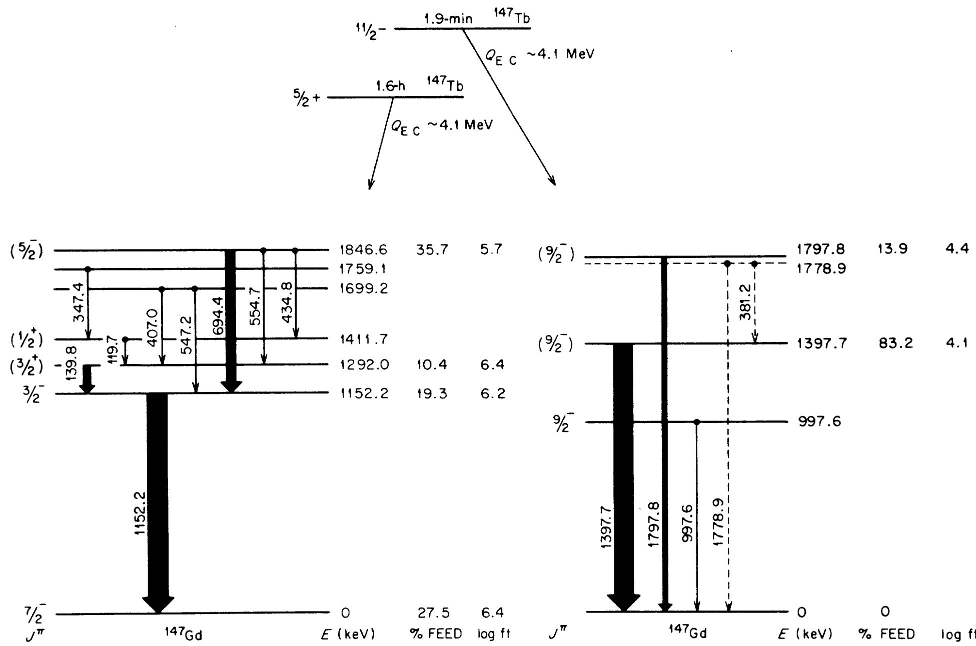

FIG. 3. Decay schemes for 1.6-h and 1.9-min ^{147}Tb.

sentially the same as the one reported by Afanasiev *et al.*[5] who derived their decay scheme on the basis of energy differences and the observation of a few sum peaks in the singles γ-ray spectrum. We were able to establish a new level at 1759.1 keV and to place the new 434.8-keV transition within the decay scheme. They proposed a possible level at 3977 keV, deexcited by the 2564- and 2684-keV transitions. Possibly because of the weak intensities of these two high-energy transitions, we did not observe them in our coincidence spectra. The difference between their energies, 119.5 keV, does, however, correspond closely to the difference between 1411.7 and 1292.0 keV, energies of the levels that are supposedly fed by the transitions in question. Logft values were calculated only for the strongly fed levels because there are undoubtedly weak transitions so far unobserved. The logft calculations were made by using a ^{147}Tb decay energy of 4.1 MeV,[15,16] and assuming only electron-capture decay. (The positron intensity is known[4,5] to be small and ~5%.) Note in Table III that our intensity for the 139.8-keV γ ray is 19.9% while Ref. 5 reports a value of 33.7%. As a result the direct feeding to the 1152.2- and 1292.0-keV levels is radically different in the two investigations.

The spin assignments of the ^{147}Gd ground state and its two lowest excited levels at 997.6 (see the discussion below) and 1152.2 keV appear to be well described[2,3] by the single-neutron orbitals $f_{7/2}$, $h_{9/2}$, and $p_{3/2}$. Logft values for the ground and 1152.2-keV states are also consistent with those assignments if the spin of the parent is indeed $\frac{5}{2}^+$. From K/L ratios for internal-conversion electrons, Afanasiev *et al.*[5] assigned multipolarities of $M1+E2$ and $E1$ to the 119.7- and 139.8-keV transitions, respectively. The parities of the levels at 1292.0 and 1411.5 keV, therefore, must be positive. In the decay of ^{145}Eu to levels in ^{145}Sm, several positive-parity states are observed[2] lying above the $\frac{3}{2}^-$ single-neutron state. One of these, well established to be $\frac{3}{2}^+$, is strongly populated in ^{145}Eu decay. A weakly populated level, connected by an $M1+E2$ transition to this $\frac{3}{2}^+$ state, appears to have a probable assign-

TABLE IV. Summary of coincidence data for 1.6-h ^{147}Tb transitions. All energies are expressed in keV.

γ rays observed	Gating transitions 119.7	139.8	554.7	694.4	1152.2
119.7		×			×
139.8	×		×		×
347.4	×	×			×
407.0		×			×
434.8	×	×			×
547.2					×
554.7		×			×
694.4					×
1152.2	×	×	×	×	

ment of $\frac{1}{2}^+$. It is on the basis of a similar pattern of direct feeding that we tentatively assign spins of $\frac{3}{2}$ and $\frac{1}{2}$ to the 1292.0- and 1411.5-keV ^{147}Gd levels, respectively. Since multipolarities for other transitions are not known, no assignments are made for the states at 1699.2 and 1759.1 keV. We do, however, propose a $\frac{5}{2}^-$ assignment for the strongly populated level at 1846.6 keV for two reasons: (1) Once again, analogously, there is a single-neutron $\frac{5}{2}^-$ state in ^{145}Sm at 1658.6 keV with a large amount of direct feeding from ^{145}Eu decay, and (2) this $\frac{5}{2}^-$ level is predicted[2] from systematics to lie at 1840 ± 50 keV in ^{147}Gd.

We would now like to discuss the decay of the $h_{11/2}$ 1.9-min ^{147}Tb isomer. As mentioned earlier, the two strongest γ rays in its decay do not correspond to any transitions seen in either the 1.6-h ^{147}Tb decay or in the ^{144}Sm$(\alpha, n\gamma)$ study.[3] However, we do see a weak 997.6-keV γ ray which decays with a 1.9-min half-life, and apparently this is the transition proceeding from the $\frac{9}{2}^-$ first excited state to the ground state in ^{147}Gd and is the most intense one observed in the in-beam investigation.[3] The two strong γ rays, 1397.7 and 1797.8 keV, seen in the 1.9-min ^{147}Tb decay were found to be coincident only with annihilation radiation. Because of this fact and because there are no other intense 1.9-min γ rays, we propose that the two transitions proceed directly to ground and establish levels at 1397.7 and 1797.8 keV. Transition energies and γ-ray intensities are summarized in Table V.

The decay scheme of the $h_{11/2}$ ^{147}Tb level is shown in Fig. 3 where it is indicated as being the isomeric state. (Based on good evidence,[18] it appears to be the isomer in ^{149}Tb as well.) In addition to the three ^{147}Gd levels at 997.6, 1397.7, and 1797.8 keV, a tentative level at 1778.9 keV has been indicated by dashed lines. This was done because two weak γ rays, 381.2 and 1778.9 keV, appear to have the correct half-life and the 381.2-keV γ ray fits as a transition between the possible 1778.9-keV level and the one at 1397.7 keV. The 1397.7- and 1797.8-keV states are both proposed to be $\frac{9}{2}^-$ on the basis of the strong direct feeding from the $h_{11/2}$ ^{147}Tb isomer and because two $\frac{9}{2}^-$ levels were predicted[2] to be located in ^{147}Gd at 1430 ± 40 and 1850 ± 50 keV. Logft values for the two states were calculated with a 4.1-MeV decay energy and by assuming only electron-capture decay, no population from higher-lying states, and that the sum of intensities for all ground state transitions represents 100% of all 1.9-min ^{147}Tb decays. It is interesting to note that it is the 1397.7-keV level that received most of the direct decay. Investigation[19] of single-neutron states in ^{143}Nd and ^{145}Sm by the (d, p) reaction indicates that, of the three $\frac{9}{2}^-$ states populated, the second one has the largest cross section. It appears then that, in ^{147}Gd as well, the 1397.7-keV level has more of the $h_{9/2}$ neutron strength and is, therefore, singled out in the decay of the $h_{11/2}$ isomeric state in ^{147}Tb.

To conclude this section we would refer the interested reader to the work of Kownacki *et al.*[3] where evidence is presented to account for the large number of ^{147}Gd levels above 1200 keV as being due to the coupling of single-neutron states to phonon excitations in the ^{146}Gd core.

D. Levels in ^{146}Gd

Because the new isotope, ^{146}Tb, is being reported for the first time, it seems appropriate to show a spectrum in which the nuclide's γ rays can be seen. Figure 4 shows a spectrum measured for a period of 40 sec after the end of bombardment. Peaks that could be assigned to specific nuclides are labeled by energy and isotope. Energies and intensities measured for the γ rays assigned to ^{146}Tb decay are listed in Table VI. Some of the weak γ rays are included because they seem to have the correct half-life and because in Ref. 10 they are assigned to transitions in ^{146}Gd. Gates were set on several of the γ rays, and the resultant coincidence information is also summarized in Table VI.

The ^{146}Tb decay scheme is shown in Fig. 5; it is based on our coincidence data and on information from the in-beam study.[10] The levels at 1579.5 keV (2^+), 2658.4 keV (4^+), and 2982.4 keV (6^+) were reported in Ref. 10. Our coincidence data confirm the existence of these states and also establish levels at 2996.9, 3099.4, and 3313.4 keV. In addition, we tentatively place a level at 3139.6 keV. Although the dynamic range covered in the coincidence measurements was insufficient to observe the 3139.6-keV γ ray we present the following arguments to substantiate the claim that this transition proceeds directly to ground. If, instead, it populated the 2658.4-keV state then the

TABLE V. Transition energies and photon intensities for 1.9-min ^{147}Tb.

E_γ (keV)	I_γ [a]
381.2 ± 0.5	~ 0.1
997.6 ± 0.4	0.9 ± 0.2
1397.7 ± 0.2	83.2 ± 5.5
1778.9 ± 0.4	2.0 ± 0.3
1797.8 ± 0.3	13.9 ± 1.4

[a] Based on the assumption that the sum of the intensities of the 997.6-, 1397.7-, 1778.9-, and 1797.8-keV transitions represents 100% of all 1.9-min ^{147}Tb decays.

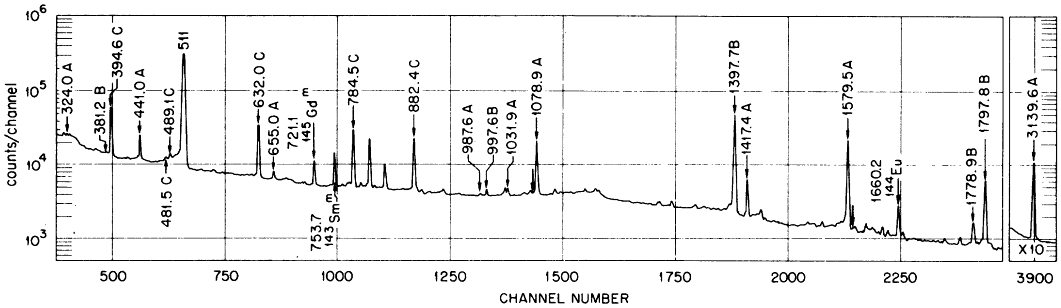

FIG. 4. γ-ray spectrum measured for a period of 40 sec after the end of bombardment of ^{141}Pr with ~110.5-MeV ^{12}C ions. The spectrum shown is actually the sum of 10 separate measurements made after the same number of 40-sec irradiations. Isotopic assignments, except where peaks are explicitly labeled, are indicated by the letters A, B, and C. Thus, A represents ^{146}Tb; B, 1.9-min ^{147}Tb; and C, 2.3-min ^{148}Tb. The two heavy arrows indicate the would-be positions of the 1073.6- and 1584.5-keV transitions in ^{146}Gd reported in Ref. 10.

estimated log*ft* for that level would be less than 3 even though the ^{146}Tb decay energy is ~7.7 MeV.[15,16] The possibility that the transition proceeds to the 1579.5-keV state cannot be excluded though it still seems unlikely that a level at 4719.1 keV should be fed with such strong intensity. Regardless of which level the 3139.6-keV γ ray proceeds from, the result is almost equal direct feeds to the 2^+ and 4^+ states so that the most probable spin of the 23-sec ^{146}Tb is 3. Log*ft* values were calculated for the states at 1579.5, 2658.4, 2996.9, 3099.4, and 3139.4 keV by assuming that the sum of the intensities of the 1579.5- and 3139.6-keV transitions represents 100% of all ^{146}Tb decays. Because of the large decay energy one would expect that positron emission should predominate over electron-capture decay; thus in calculating log*ft* values only β^+ decay was considered.

TABLE VI. Summary of transition and coincidence data for 23-sec ^{146}Tb.

Transition data		Gating transitions (keV)			
E_γ (keV)	I_γ	441.0	1078.9	1417.4	1579.5
324.0 ± 0.3 [a]	0.8 ± 0.3				
441.0 ± 0.1	13.1 ± 0.9		×		×
655.0 ± 0.2	2.6 ± 0.3		×		×
987.6 ± 0.4 [a,b]	1.0 ± 0.3				
1031.9 ± 0.4 [a,b]	2.9 ± 0.3				
1078.9 ± 0.2 [a]	51.6 ± 2.6	×			×
1417.4 ± 0.3	17.2 ± 1.1				×
1579.5 ± 0.2 [a]	100 [c]	×	×	×	
3139.6 ± 0.4	11.7 ± 0.8				

[a] γ rays observed in the in-beam experiments reported in Ref. 10.
[b] Transitions not included in the decay scheme shown in Fig. 5.
[c] Intensities are normalized to a value of 100 for the 1579.5-keV transition.

Kownacki *et al.*[10] have made an extensive examination of states in ^{144}Sm and ^{146}Gd; qualitatively, at least, the majority of these states can be explained on the basis of two-quasiparticle configurations. We would like to concentrate on one apparent inconsistency which has to do with the lowest-lying 3^- state in the $N = 82$ isotones. This state starts out at 3279 keV in ^{136}Xe and drops precipitously as Z increases. In ^{144}Sm it is located at 1810 keV and is strongly fed by a transition from the 4^+ state at 2191 keV. In turn it

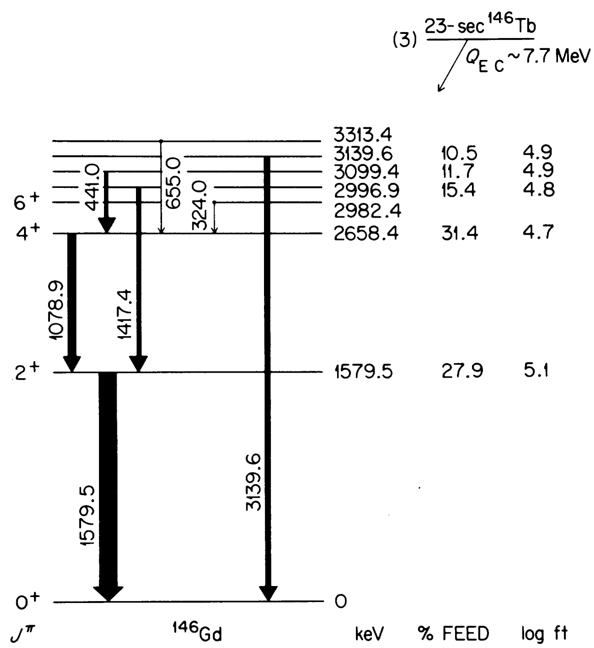

FIG. 5. Decay scheme for the new isotope ^{146}Tb. The possibility that the 3139.6-keV transition feeds the 1579.5-keV level instead of proceeding directly to ground cannot be excluded.

deexcites primarily to the 2^+ state at 1660 keV and very weakly to ground. The situation in ^{146}Gd seems to be quite different—a strongly populated 3^- state has not been found.[10,20] Instead, Kownacki *et al.*[10] tentatively propose a state only 5 keV above the 2^+ level as being the "missing" 3^- state. They point out that this location fits reasonably well with systematics for the $N=82$ isotones. However, the $E1$, 1073.6-keV transition from the 4^+ state has an intensity which is 27.6 times less than the intensity of the $E2$, 1078.5-keV transition to the 2^+ level. In ^{144}Sm the comparable $E1$, 380.5-keV transition is 1.7 times more intense than the $E2$, 530.6-keV transition.

We were able to observe neither the 1073.6-keV transition nor the 1584.5-keV transition to ground reported in Ref. 10. According to Ref. 10 the intensity of the 1073.6-keV transition is 3.6% relative to that of the 1078.5-keV transition; on the same scale we would say that the 1073.6-keV γ-ray intensity is <1.5%. Again from Ref. 10 the 1584.5-keV γ-ray intensity relative to that of the 1579.5-keV transition should be 1.7%; our limit is <0.5%. A search was made for two γ rays whose energies would sum to 1078.9 keV in case the 3^- level, although still located between the 2^+ and 4^+ states, were in reality at a higher energy than that proposed by Kownacki *et al.*[10] None were found. It is puzzling that the ^{146}Tb decay which directly populates 2^+ and 4^+ states should for some reason miss a 3^- state. The possibility that the 1078.9- and 1579.5-keV γ rays are in reality $E2$ and $E1$ doublets is ruled out by angular-correlation[10] and conversion-coefficient[20] measurements. Both experiments show that the transitions are $E2$ in character. An alternative explanation may be that the systematic drop in excitation energy of the 3^- state is reversed at ^{146}Gd. As noted by Kownacki *et al.*[10] three other trends are disrupted at $Z=64$ for the $N=82$ isotones: (1) The first 2^+ state which increases in energy from ^{136}Xe to ^{144}Sm suddenly drops from 1660-keV (^{144}Sm) to 1580-keV energy (^{146}Gd); (2) the lowest 4^+ and 6^+ states both increase sharply in excitation energy at ^{146}Gd; and (3) the energy spacing between the 4^+ and 6^+ states (and, of course, between the 2^+ and 4^+ levels as well) is much greater in ^{146}Gd than in the other isotones. The authors[10] attribute these differences to the fact that the $d_{5/2}$ proton subshell is filled at $Z=64$. If the 3^- state in ^{146}Gd does indeed lie above the 4^+ and 6^+ states (as it does in ^{136}Xe, ^{138}Ba, and ^{140}Ce) then a likely candidate would be the strongly populated level at 2996.9 keV which deexcites by means of the 1417.4-keV transition to the 2^+ first excited state.

E. Conclusion

The present investigation confirms the data reported in Ref. 7 on the decay scheme of 2.3-min ^{148}Tb and on the existence of a 1.9-min high-spin isomer in ^{147}Tb. This latter point establishes the anticipated[17] crossing in excitation energy of the $h_{11/2}$ and $g_{7/2}$ proton orbitals at $Z=65$ for odd-A isotopes with $N=82$. It is gratifying to note that the predictions from our earlier survey[2] of available data for $N=83$ isotones seem to agree with what one finds experimentally for levels in ^{147}Gd. The investigation of ^{149}Dy levels populated in ^{149}Ho decay should be quite interesting. Such a task has now been made somewhat easier by the added confidence obtained from the present work on ^{147}Tb decay. One way to shed light on the question of the lowest 3^- state in ^{146}Gd would be to investigate levels in ^{148}Dy. Determination of excitation energies for its first 2^+, 4^+, and 6^+ states could also help elucidate the influence of the subshell closure at $Z=64$ on the level spacings of $N=82$ isotones.

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*On leave from the II. Physikalisches Institut der Universität Göttingen, Germany. Present address since June 1, 1972: Oak Ridge National Laboratory.

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[1]B. H. Wildenthal, E. Newman, and R. L. Auble, Phys. Rev. C 3, 1199 (1971).

[2]E. Newman, K. S. Toth, and I. R. Williams, Phys. Rev. C 7, 290 (1973).

[3]J. Kownacki, H. Ryde, V. O. Sergejev, and Z. Sujkowski, Phys. Scr. 5, 66 (1972).

[4]Y. Y. Chu, E. M. Franz, and G. Friedlander, Phys. Rev. 187, 1529 (1969).

[5]V. P. Afanasiev, I. I. Gromova, G. I. Iskhakov, V. V. Kuznetsov, M. Ya. Kuznetsova, and N. A. Lebedev, Izv. Akad. Nauk SSSR Ser. Fiz. 35, 719 (1971) [transl.: Bull. Acad. Sci. USSR Phys. Ser. 35, 659 (1971)].

[6]R. Arlt, G. Bayer, V. V. Kuznetsov, V. Neubert, A. V.

Potempa, U. Hagemann, and E. Hermann, Izv. Akad. Nauk SSSR Ser. Fiz. 35, 1612 (1971) [transl.: Bull. Acad. Sci. USSR Phys. Ser. 35, 1470 (1971)].

[7]W. W. Bowman, D. R. Haenni, and T. T. Sugihara, Phys. Rev. C 7, 1686 (1973).

[8]R. D. Macfarlane and R. D. Griffioen, Nucl. Instrum. Methods 24, 461 (1963).

[9]W-D. Schmidt-Ott, R. L. Mlekodaj, and C. R. Bingham, Nucl. Instrum. Methods 108, 13 (1973).

[10]J. Kownacki, H. Ryde, V. O. Sergejev, and Z. Sujkowski, Nucl. Phys. A196, 498 (1972).

[11]Ts. Vylov, K. Ya. Gromov, I. I. Gromova, G. I. Iskhakov, V. V. Kuznetsov, M. Ya. Kuznetsova, A. V. Potempa, and M. I. Fominykh, Dubna Report No. P6-6512 (unpublished).

[12]K. Krien, F. Djadali, R. A. Naumann, H. Hübel, and E. H. Spejewski, Phys. Rev. C 7, 2484 (1973).

[13]A. Hashizume, Y. Tendow, and T. Katou, in Proceedings of the Symposium on High-Spin Nuclear States and Related Phenomena, Stockholm, 1972 (unpublished).

[14]R. Arlt, V. V. Kuznetsov, V. Neubert, L. K. Peker, A. V. Potempa, and U. Hagemann, Izv. Akad. Nauk SSSR Ser. Fiz. 36, 2074 (1972) [transl.: Bull. Acad. Sci. USSR Phys. Ser. 36, 1826 (1972)].

[15]N. Zeldes, A. Grill, and A. Simievic, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 3, No. 5 (1967).

[16]W. D. Myers and W. J. Swiatecki, Nucl. Phys. 81, 1 (1966); Lawrence Berkeley Laboratory Report No. UCRL-11980 (unpublished).

[17]E. Newman, K. S. Toth, R. L. Auble, R. M. Gaedke, M. F. Roche, and B. H. Wildenthal, Phys. Rev. C 1, 1118 (1970).

[18]R. D. Macfarlane, Phys. Rev. 126, 274 (1962).

[19]P. R. Christensen, B. Herskind, R. R. Borchers, and L. Westgaard, Nucl. Phys. A102, 481 (1967).

[20]B. Spoelstra, Nucl. Phys. A174, 63 (1971).