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Observation of a 1^+ $(\pi h_{11/2}, \nu h_{9/2})$ state in ^{148}Tb populated in the decay of a new isotope, ^{148}Dy†

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A new activity with a half-life of 3.1 ± 0.1 min was observed in bombardments of ^{142}Nd with ^{12}C ions accelerated in the Oak Ridge isochronous cyclotron. A gas-jet-capillary system was used to transport product nuclei to a shielded area so that singles and coincidence γ-ray measurements could be made. Only one transition, 620.2 ± 0.1 keV, was found to be associated with this new activity. It was assigned to ^{148}Dy because (1) the variation of its yield as a function of bombarding energy was the same as for ^{148}Tb γ rays, indicating that an equal number of nucleons were evaporated from the compound system, and (2) it was found to be in coincidence with terbium K x rays. No γ rays were observed in its coincidence spectrum, and no initial growth period was seen for transitions that follow the decay of the ^{148}Tb high-spin isomer. For these reasons the transition very probably proceeds directly to the low-spin isomeric state in ^{148}Tb and establishes an intermediate level at ~620 keV. The spin and parity of this level has to be 1^+ because the transition from the 0^+ ^{148}Dy ground state has a logft value of 3.9. Our suggestion is that this allowed β decay connects states with the following characters: 0^+ $(\pi h_{11/2}, \pi h_{11/2}) \rightarrow 1^+$ $(\pi h_{11/2}, \nu h_{9/2})$. γ-ray data were also obtained for ^{149}Dy and ^{149}Tb^m. From this information the half-life of ^{149}Dy was determined to be 4.1 ± 0.2 min, a value which agrees with recent half-lives reported for this isotope.

[RADIOACTIVITY ^{148}Dy, ^{149}Dy, ^{149}Tb^m; measured $T_{1/2}$, E_γ, I_γ, $\gamma\gamma$ coin; discovered new isotope ^{148}Dy; ^{148}Tb, ^{149}Gd deduced levels, J, π.]

I. INTRODUCTION

The impetus behind the present study was the investigation of the decay of the so-far unreported nuclide ^{147}Dy to levels in ^{147}Tb, an $N=82$ nucleus. The level structure of 82-neutron odd-A nuclei is of interest because the assumption of a doubly magic $N=82$, $Z=50$ core allows detailed microscopic calculations[1] to be made concerning their nuclear properties. Up to now, however, the (EC/β^+) decay modes of dysprosium isotopes with $A<152$ have not been extensively studied. In particular, before this investigation was begun, ^{148}Dy had not been observed and the only information available for ^{149}Dy was its half-life (see Ref. 2 for the most recent values). As part of a search for ^{147}Dy it was therefore imperative to: (1) discover ^{148}Dy, (2) study its decay characteristics, and (3) ascertain the main γ rays following the decay of ^{149}Dy.

The dysprosium nuclides were produced by bombarding ^{142}Nd with ^{12}C, even though published data[3] indicated that the maximum incident energy available from the Oak Ridge isochronous cyclotron (ORIC) was insufficient to reach the peak of the ^{142}Nd(^{12}C, $7n$)^{147}Dy excitation function. Given the ORIC parameters, two other projectile-target combinations, i.e. 160-MeV ^{14}N + ^{141}Pr and 202-MeV ^{16}O + ^{140}Ce, could provide the needed compound-nuclear excitation energy. The intensities, however, of these ^{14}N^{5+} and ^{16}O^{6+} beams are much less than that of the ^{12}C^{4+} beam. Thus, for this "survey" experiment the more intense ^{12}C beam was chosen.

II. EXPERIMENTAL METHOD

The experimental assembly utilized the helium gas-jet technique[4], the basis for which is that 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. In the present investigation, a capillary transport system was used to extract the products from the gas-jet reaction chamber (see Ref. 5 for a schematic drawing) to a shielded area where γ ray counting could be made. The recoils were collected on a catcher foil located inside a 500-cm^3 chamber (described in Ref. 6). Preliminary measurements were made by rotating the catcher foil to a position in front of a Ge(Li) detector. Once it was determined that the half-lives of the observed activities were long enough the following procedure was put into effect. After a suitable bombardment time, the cyclotron beam was turned off, the collection chamber was opened, the catcher foil was removed and placed close to two Ge(Li) detectors in a geometry optimum for γ-γ coincidence measurements. While the counting was being done, the bombardment and collection cycle was repeated with a fresh catcher foil.

Singles and coincidence γ-ray spectra were measured simultaneously. The coincidence data were digitized with the ORIC analog-to-digital-converter system which has a 9000-channel resolution capability and is interfaced to an in-house computer. The data were stored in a three-word (γ-γ-τ) list mode on discs with million-word capacities. Singles spectra were taken at the same time with another smaller computer system which could be programmed in a spectrum multiscale mode. In this way repeated cycles of singles spectra were accumulated in a number of time bins to provide half-life information. All data were transferred onto magnetic tapes for permanent storage. These were later scanned and the data analyzed with computer codes to determine energies, intensities and half-lives, and spectra in coincidence with prominent γ-ray peaks.

The target consisted of a ~250-μg/cm^2 neodymium oxide layer (enriched in ^{142}Nd to 97.7%) electrodeposited onto a 25-μm beryllium foil. The ^{12}C beam deflected out of the ORIC had an energy of ~118 MeV. However, the beryllium backing foil served as the entrance window to the gas-jet reaction chamber so that it intercepted the beam first. The maximum energy on target was, therefore, ~111 MeV. This energy was selected for the half-life and coincidence measurements because (on the basis of published data[3]) it should correspond closely to the peak of the ^{142}Nd(^{12}C, 6n)^{148}Dy excitation function. In addition, at the same energy, the ^{142}Nd(^{12}C, 5n)^{149}Dy reaction cross section[3] is down by only a factor of 2 from its peak value. To aid in mass assignments, relative γ-ray yields were measured as a function of bombarding energy with the use of beryllium degrader foils.

III. ^{148}Dy

In an earlier study[7] we had bombarded ^{141}Pr with ^{12}C ions to investigate the light terbium isotopes, $^{146-148}$Tb. That information provided us with useful cross-bombardment data. Most of the new γ rays observed in the present study were eventually assigned, either tentatively or with certainty to ^{149}Dy. (These will be discussed in Sec. IV.) One intense γ ray, 620.2 ± 0.1 keV, that had not been seen previously[7] was found to have a half-life of 3.1 ± 0.1 min. On the basis of evidence to be described below, it became clear that this new activity was ^{148}Dy.

Figure 1 shows yields measured as a function of bombarding energy for the 620.2-keV γ ray and for two of the strong transitions known[7] to follow the decay of 2.3-min ^{148}Tb. The three sets of yield curves are very similar in shape, indicating that the 620.2-keV γ ray belongs to a nuclide with $A = 148$. For comparison we have included the yield curve for the most intense (see e.g. Ref. 8) ^{149}Tb^m γ ray. Excitation functions measured[3] for (^{12}C, 3n), (^{12}C, 4n), and (^{12}C, 5n) reactions induced on ^{142}Nd peak at 67, 80, and 95 MeV, respectively. As can be noted in Fig. 1 the yield curve for the 620.2-keV γ ray appears to be turning over at 111 MeV; in light of the previous data[3] this information is consistent with the γ ray being due to the ^{142}Nd(^{12}C, 6n) product.

The spectrum in coincidence with the 620.2-keV

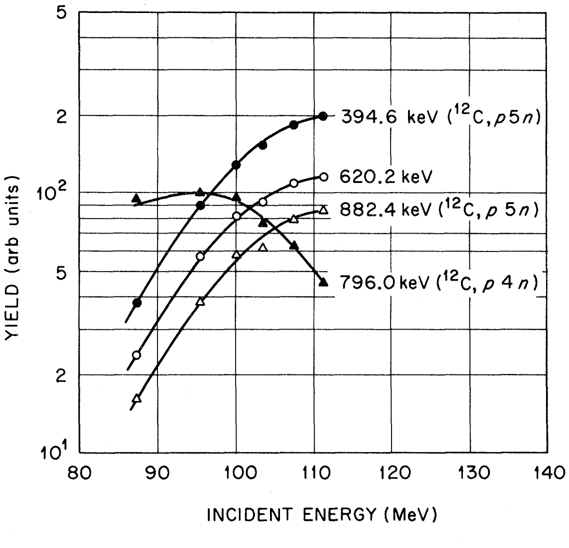

FIG. 1. Yields as a function of bombarding energy for the following γ rays: (1) 394.6 keV (^{148}Tb); (2) 882.4 keV (^{148}Tb); (3) 796.0 keV (^{149}Tb^m); and (4) 620.2 keV (assigned to the new isotope ^{148}Dy).

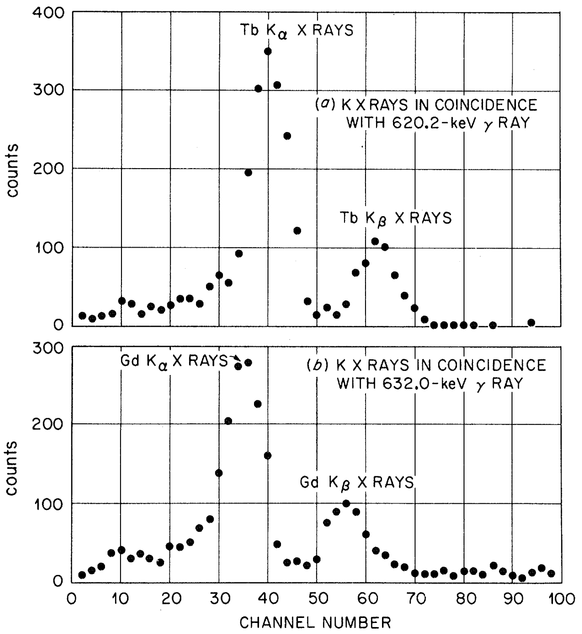

FIG. 2. K x rays observed in coincidence with the 620.2-keV [part (a)] and 632.0-keV [part (b)] transitions. The 632.0-keV γ ray, known to follow the decay of ^{148}Tb, is in coincidence with gadolinium x rays, while the new 620.2-keV γ ray is in coincidence with terbium x rays. This Z identification supports the proposal that the 620.2-keV γ ray belongs to the decay of a dysprosium isotope.

γ ray showed only the annihilation radiation peak and K x rays. In Fig. 2 we display the x-ray regions of spectra in coincidence with the 620.2-keV transition and with a 632.0-keV γ ray which is known[7] to be due to ^{148}Tb. The coincidence data were stored with amplifier gains set so that there were ~0.29 keV per channel. For the rare earths under discussion this corresponds to a difference of ~5 and 6 channels between $K\,\alpha$ and $K\,\beta$ x rays, respectively, for adjacent elements. Differences of about those magnitudes are indeed observed in the spectra shown in Fig. 2. (Note that for display purposes each point represents two channels.) The 620.2-keV transition, in coincidence with terbium x rays, is therefore due to an isotope of dysprosium. This unequivocal Z identification coupled with the evidence that the activity is produced by the evaporation of six nucleons from the compound system means that the new nuclide is ^{148}Dy.

Figure 3 shows the proposed decay scheme for ^{148}Dy, a doubly-even nucleus whose ground state spin assignment is undoubtedly 0^+. Because no γ rays were seen in coincidence with the 620.2-keV transition it cannot be part of a cascade proceeding from a low-spin state (fed directly in the decay of ^{148}Dy) to the high-spin, probably 9^+, ^{148}Tb isomer.[7,8] Also, during the preliminary experiments to determine half-lives of the observed activities bombardment times were varied from 10 sec to 3 min and counting was started almost immediately after irradiation. None of the 2.3-min ^{148}Tb γ rays showed any initial growth periods; this is more evidence that the high-spin isomer is not fed in the decay of ^{148}Dy. For these reasons we have indicated in Fig. 3 the 620.2-keV transition as proceeding directly to the low-spin 66-min ^{148}Tb isomer. In this instance, however, it is

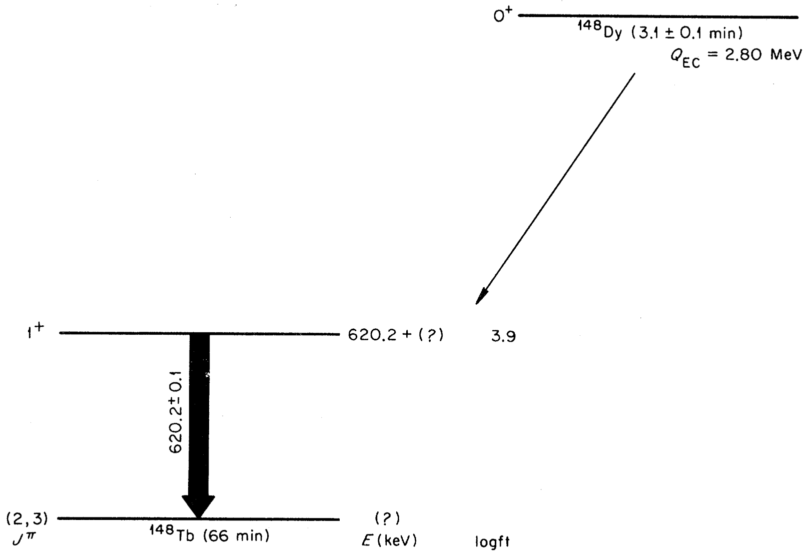

FIG. 3. Proposed decay scheme for the new isotope ^{148}Dy. Arguments are presented in the text suggesting that the $0^+ \rightarrow 1^+$ β transition connects states with the following characteristics: $(\pi h_{11/2}, \pi h_{11/2}) \rightarrow (\pi h_{11/2}, \nu h_{9/2})$.

conceivable that a low-energy coincident γ ray was not observed due to a combination of two reasons: (1) the transition would have a high probability for internal conversion, and (2) the timing characteristics of the coincidence circuitry were such that low-energy pulses were found to be attenuated. Thus, a low-lying intermediate state cannot be ruled out. An attempt to establish a parent-daughter relationship between ^{148}Dy and the low-spin ^{148}Tb isomer was not made because its two intense γ rays[9] are also seen in the decay of the high-spin isomer whose production is much more probable in a heavy-ion-induced reaction. Chances of observing an initial growth period for these two γ rays would, therefore, be extremely improbable. Note that in Fig. 3 the excitation energy of the low-spin isomer is indicated by a question mark because it is not known which of the two isomers represents the ground state in ^{148}Tb.

The spin of 66-min ^{148}Tb is not certain. An assignment of 2^- has been suggested.[9] The log*ft* value, however, for the β decay to a 4^+ state in ^{148}Gd is only 6.9. This number is much too small for a first-forbidden unique transition which according to recently proposed[10] rules must have a log*ft* value of ≥ 8.5. On that basis, a spin of 3 seems to be more probable unless the decay scheme reported in Ref. 9 is not completely correct. In either case there should be little or no direct feed to this state from ^{148}Dy. Instead, one can safely assume that the bulk of ^{148}Dy decay proceeds through the level deexcited by the 620.2-keV transition and the resultant log*ft* value is ~3.9. Then according to the selection rules proposed in Ref. 10 the β decay is allowed and the spin assignment for the level must be 1^+ because a $0^+ \rightarrow 0^+$ transition is isospin forbidden and would have a log*ft* value ≥ 6.5.

Similar situations have been reported for ^{152}Dy (Ref. 11) and ^{150}Dy (Ref. 12), i.e., only one transition is associated with each nuclide, leading to the conclusion that their β decays are allowed and proceed entirely through 1^+ states in their respective terbium daughters. An interesting question has been raised by Devous and Sugihara concerning this 1^+ state in ^{152}Tb. Their data indicate the 1^+ state is single particle in character, while earlier work,[13] dealing with the decay scheme of the ^{152}Tb high-spin isomer, suggests that ^{152}Tb levels are best described as being deformed. (The 8^+ isomer itself is proposed[13] to result from the coupling of $\pi\frac{5}{2}^-[532]$ and $\nu\frac{11}{2}^-[505]$ Nilsson orbitals.) The 256.8-keV *E*1 transition, connecting the 1^+ level with the 2^- ground state, should be strongly hindered if the two states do in fact differ greatly in deformation. Devous and Sugihara,[11] however, found no appreciable hindrance for the 256.8-keV transition and concluded that their data were inadequate to explain the nature of the 1^+ state in ^{152}Tb.

^{148}Dy and ^{148}Tb, with 82 and 83 neutrons, respectively, can be described as spherical nuclei. The ground state of ^{148}Dy is likely to be built up mainly of two $h_{11/2}$ protons coupled to a spin of 0 because the neutrons are in a closed-shell configuration and the $d_{5/2}$ proton subshell is filled at

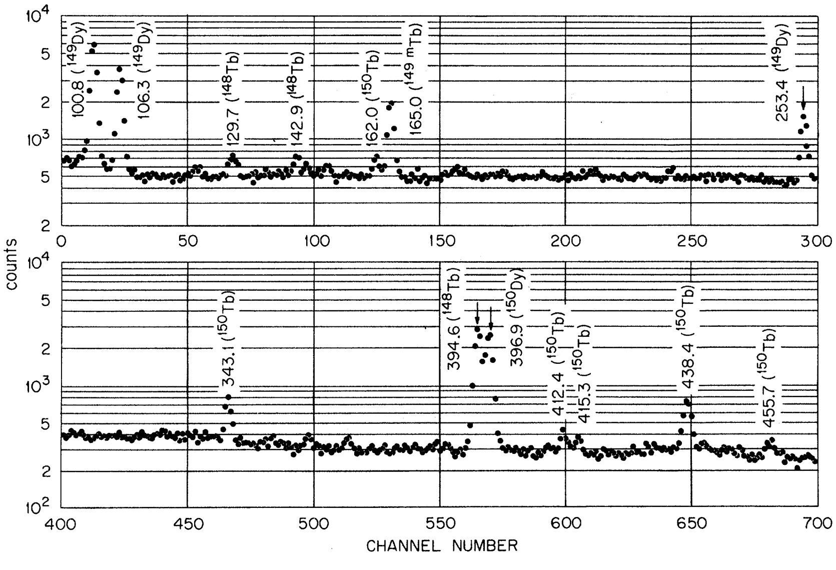

FIG. 4. Portions (100–460 keV) of γ-ray spectra measured at ^{12}C bombarding energies of 82.3 and 95.5 MeV. The two spectra were summed to emphasize $A = 149$ nuclides. Note the 396.9-keV γ ray which is assigned to the electron-capture decay of the well-established α emitter, ^{150}Dy.

gadolinium ($Z=64$). For ^{148}Tb the available low-lying proton orbitals are $d_{5/2}$, $h_{11/2}$, $g_{7/2}$, $s_{1/2}$, and $d_{3/2}$ (see Ref. 1 for a discussion of proton states of odd-Z $N=82$ nuclei). The first available 83rd neutron orbital is expected to be $f_{7/2}$, followed in turn by the $h_{9/2}$ and $i_{13/2}$ orbitals. Therefore, to obtain a positive parity state in ^{148}Tb one must couple the $h_{11/2}$ proton to the odd neutron since the remaining proton states have even l values. Indeed, the ^{148}Tb high-spin isomer is proposed[7,8] to be ($\pi h_{11/2}$, $\nu f_{7/2}$) in character. We would like to suggest that the 1^+ state in ^{148}Tb is the result of coupling the $h_{11/2}$ proton to the next available neutron orbital, i.e., $h_{9/2}$. This accounts for the observed ^{148}Dy allowed β transition since it would then connect the following two-quasiparticle states: $(\pi h_{11/2}, \pi h_{11/2}) \rightarrow (\pi h_{11/2}, \nu h_{9/2})$.

It seems reasonable to describe the ^{150}Tb 1^+ state (see Ref. 12) in the same fashion because: (1) ^{150}Tb is only 3 neutrons away from the closed shell, and (2) the decay scheme of the high-spin isomer in ^{150}Tb is such that it also appears[14] to be 9^+ and ($\pi h_{11/2}$, $\nu f_{7/2}$) in character. One is then tempted to apply the same explanation to the 1^+ 256.8-keV state in ^{152}Tb. The excitation energy of this ($\pi h_{11/2}$, $\nu h_{9/2}$) level would then increase smoothly, from 256.8 to ~397 (see Ref. 12) to ~620 keV, as the $N=82$ shell is approached. The description, however, still does not answer the question raised by Devous and Sugihara[11] as to why the 256.8-keV $E1$ transition to the 2^- ground state is not hindered. One explanation is that the 1^+ and 2^- levels are both good single-particle states, in contrast to other levels observed[13] in ^{152}Tb. Evidence for shape coexistence of this type has been found[15] in the neighboring odd-Z nucleus ^{151}Eu, where the low-lying states at 0, 22, and 197 keV have the shell-model configurations $d_{5/2}$, $g_{7/2}$, and $h_{11/2}$, respectively. The ^{153}Eu(p, t) reaction, however, populates with a large cross section a level at 261 keV which is described[15] as being due to the deformed $\frac{5}{2}^+[413]$ orbital. Without further data, shape coexistence in ^{152}Tb is of course only a speculation, but one which does account for the available evidence. We might add that two combinations of single-particle orbitals could give rise to a 2^- spin assignment, i.e., ($\pi d_{5/2}$, $\nu h_{9/2}$) and ($\pi d_{3/2}$, $\nu f_{7/2}$).

IV. ^{149}Dy and ^{149}Tb^m

As mentioned earlier, most of the new γ rays whose nuclidic assignments could be determined with some certainty follow the decay of ^{149}Dy. Prior to this investigation only its half-life had been reported, the latest values[2] being 4.6 ± 0.4 min from x-ray decay-curve analyses and 5.1 ± 0.9 min from the initial growth period observed in the

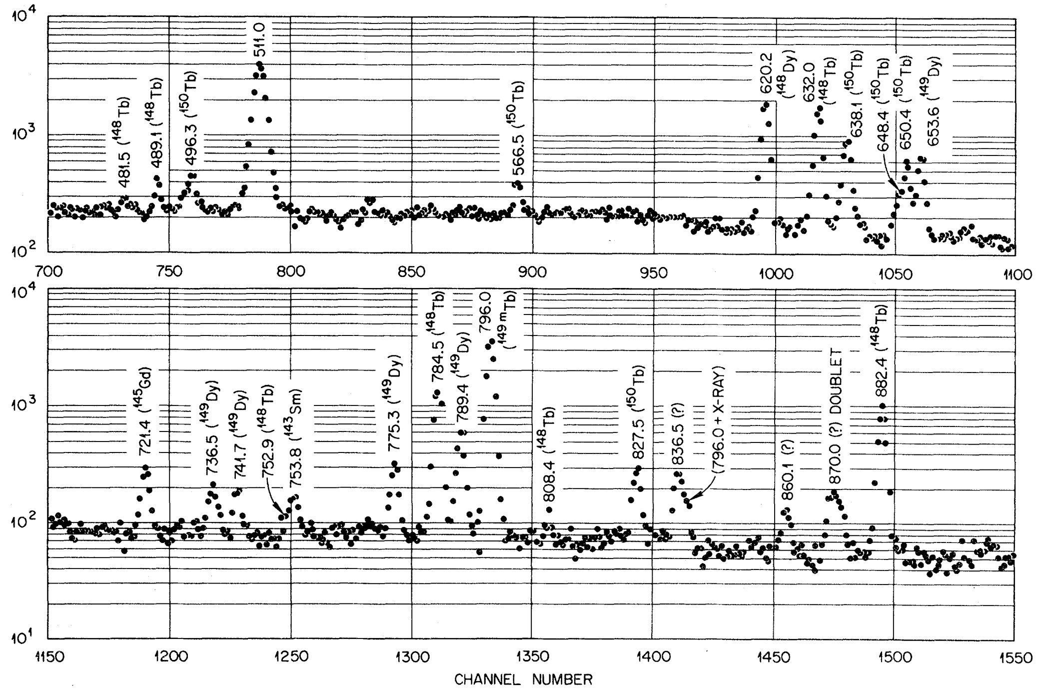

FIG. 5. Portions (460–900 keV) of γ-ray spectra measured at ^{12}C bombarding energies of 82.3 and 95.5 MeV. The two spectra were summed to emphasize $A=149$ nuclides. Note the 620.2-keV γ ray, assigned to the new isotope, ^{148}Dy.

TABLE I. Summary of transition and coincidence data for ^{149}Dy.

Transition data		Gating transitions (keV)		
E_γ (keV)	I_γ	100.8	106.3	253.4
100.8 ± 0.1	100 [a]		X	X
106.3 ± 0.1	51.1 ± 2.6	X		X
253.4 ± 0.1	49.6 ± 5.0	X	X	
653.6 ± 0.1	59.5 ± 6.0			
736.5 ± 0.1	19.2 ± 3.0	X		
741.7 ± 0.1	17.3 ± 2.6	?		
775.3 ± 0.1	34.7 ± 3.5	X	X	
789.4 ± 0.1	65.0 ± 6.5			
1274.2 ± 0.3	18.1 ± 3.9	X	X	X
1776.5 ± 0.3	78.6 ± 11.9	X		
1806.2 ± 0.3	64.1 ± 9.6			

[a] Photon intensities normalized to a value of 100 for the 100.8-keV transition.

TABLE II. Summary of transition and coincidence data for ^{149}Tb^m.

Transition data		Gating transitions (keV)		
E_γ (keV)	I_γ	165.0	632.0 [a]	796.0
165.0 ± 0.1	7.5 ± 0.5		X	
630.7 ± 0.3	~2.9	X		
796.0 ± 0.1	100 [b]			

[a] Gating peak due mainly to the 632-keV ^{148}Tb γ ray.

[b] Photon intensities normalized to a value of 100 for the 796.0-keV transition.

decay of the ^{149}Tb 3.967-MeV α group. Several problems were encountered in determining assignments. First, the coincidence and half-life measurements were not made at the optimum bombarding energy for $A = 149$ isotopes. Second, the half-lives of ^{149}Dy and ^{149}Tb^m are similar. (^{150}Tb, with a half-life of 5.8 min was also a potential problem but in this instance the data reported in Ref. 14 were used to identify its γ rays.) Third, the yield curve measurements covered a photon energy range of only up to ~900 keV because they were directed chiefly toward assigning the 620.2-keV transition. For these reasons many new γ rays, especially those with energies $\geq$800 keV, were left unassigned. Since much of the γ-ray data to be discussed below is new it seems appropriate to show a spectrum wherein the $A = 149$ nuclides are emphasized. For this purpose the spectra observed at 82.3 and 95.5 MeV during the yield measurements were summed and are shown in Figs. 4 and 5. Note the ^{150}Dy 396.9-keV (Fig. 4) γ ray reported in Ref. 12 and the ^{148}Dy 620.2-keV (Fig. 5) transition discussed in the previous section.

Table I summarizes the energies and photon intensities of γ rays assigned to ^{149}Dy. Three of these, 100.8, 106.3, and 253.4 keV, were intense enough so that spectra in coincidence with them could be projected out. This information is also included in Table I. The assignment of the three transitions to ^{149}Dy is based on half-lives, yield-curve measurements, and coincidence data (in particular the fact that terbium K x rays were observed). From the decay of these γ rays the half-life of ^{149}Dy was found to be 4.1 ± 0.2 min in agreement with the results of Ref. 2. This half-life value was an important criterion for assigning the remaining γ rays listed in Table I for the following reason. Two γ rays known to belong to ^{149}Tb^m were found to decay with a half-life of $\geq$6.0 min in contrast to its previously reported half-lives of 4.0 min (Ref. 8), 4.2 min (Ref. 2), and 4.5 min (Ref. 16). This apparent increase in half-life is taken to mean that ^{149}Dy, with a probable ground state spin of $\frac{7}{2}^-$ (due to the $f_{7/2}$ 83 neutron), feeds into both the ^{149}Tb $d_{5/2}$ ground state and its $h_{11/2}$ isomer. (Evidence that the 4-min species is the isomer has been presented in Ref. 17.) The decay scheme of ^{149}Dy is undoubtedly complex, with many more transitions following its decay than are listed in Table I. We have not attempted to put together a level scheme though on the basis of the coincidence data one could propose levels at 100.8, 207.1, 460.5, 837.3, 982.4, 1734.7, and 1877.3 keV. Additional information is necessary, however, to determine if these levels are superimposed on the ground or isomeric state of ^{149}Tb.

Table II summarizes the ^{149}Tb^m transition energies, photon intensities, and coincidence information. The 630.7-keV γ ray, whose presence had earlier[16] only been inferred, was observed in and its energy determined from the spectrum in coincidence with the 165.0-keV γ ray. The 632-keV gate, as indicated in Table II, was due mainly to the ^{148}Tb γ ray of that energy; nevertheless, the 165.0-keV transition was clearly seen. The 796.0-keV transition was found to be in coincidence only with x rays and annihilation radiation; the γ ray's large intensity and this coincidence information strongly suggest that the 796.0-keV transition proceeds directly to ground. Figure 6 shows the partial decay scheme for ^{149}Tb^m. Aside from photon intensities it is the same as that proposed by Arlt *et al.*[16] on the basis of singles γ-ray measurements. Much of the decay proceeds through the level at 796.0 keV with an allowed logft value of ~4.2. The situation is similar to the decay of the high-spin ^{147}Tb 1.9-min state, where some 84% of the direct decay populates[7] a level at 1397.7 keV. As in that case we would suggest that the ^{149}Tb^m decay to the 796.0-keV level con-

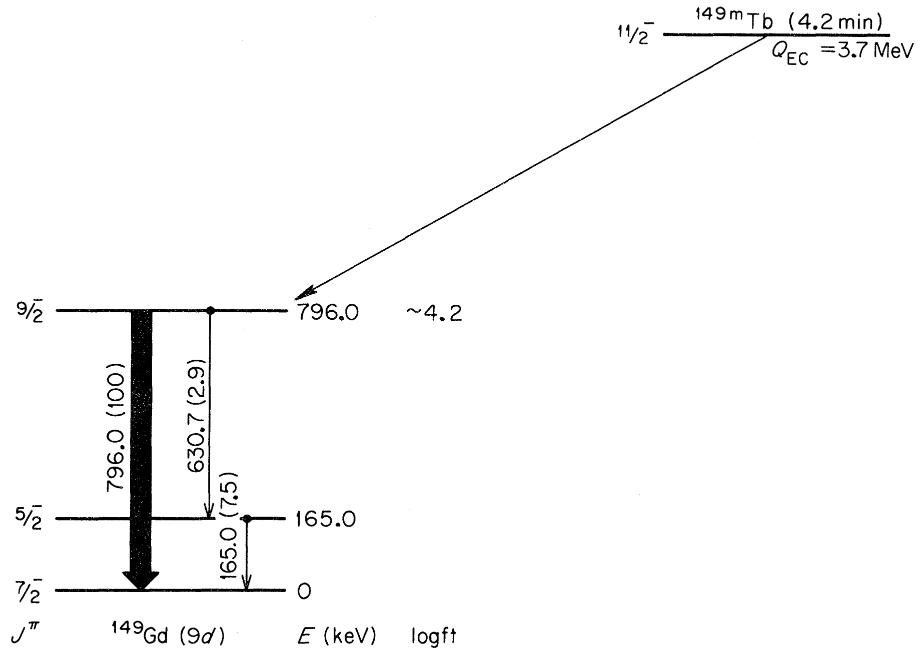

FIG. 6. Proposed decay scheme for ^{149}Tb^m. The allowed β transition to the ^{149}Gd 796.0-keV level is suggested to proceed between states with the following characteristics: $\pi h_{11/2} \rightarrow \nu h_{9/2}$.

nects the following states, $\pi h_{11/2} \rightarrow \nu h_{9/2}$. The ground state of ^{149}Gd has been measured[18] to be $\frac{7}{2}$ and is probably due to the odd neutron being in the $f_{7/2}$ orbital. The spin of the 165.0-keV level has been proposed[19] to be $\frac{5}{2}^-$; the assignment is consistent with the present results. As in the case of ^{149}Dy, our data indicate that ^{149}Tb^m has additional γ rays in its decay. None of the possible transitions, however, are intense enough to change appreciably the logft value for the β transition to the 796.0-keV level.

V. CONCLUSION

No strong γ ray was observed that could be ascribed to the expected $M4$ isomer in ^{147}Dy. (It is seen in other $N = 81$ isotones ranging from ^{133}Te to ^{145}Gd, see e.g. Ref. 20.) Contrastingly, the 721- and 753-keV $M4$ isomeric transitions in ^{145}Gd and ^{143}Sm, respectively, were observed. In addition, ^{147}Tb γ rays were also seen. The indication is that sufficient energy was available to produce $A = 147$ nuclides even though it was estimated to be ~15 MeV below the maximum of the (^{12}C, 7n) excitation function. Aside from the energetics involved two other possibilities exist that could explain why ^{147}Dy^m was not seen. First, for nuclei far from stability, the cross section for the (^{12}C, 7n) reaction could be much less than that of the (^{12}C,p6n) reaction. The ^{148}Dy yield was found to be ~30% less than that for the high-spin ^{148}Tb isomer. The necessity to evaporate an additional neutron could depress the ^{147}Dy cross section even further *vis à vis* the one for ^{147}Tb. Second, the ^{147}Dy isomeric transition is perhaps weaker compared to the direct decay to ^{147}Tb, via the following β transition, $\nu h_{11/2} \rightarrow \pi h_{11/2}$. One obviously needs to reach the maximum of the production cross section for $A = 147$ nuclides before the alternatives can be examined further.

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

[2] C. R. Bingham, D. U. O'Kain, K. S. Toth, and R. L.

Hahn, Phys. Rev. C 7, 2575 (1973).

[3] J. M. Alexander and G. N. Simonoff, Phys. Rev. 133, B93 (1964).

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

[5] K. S. Toth, R. L. Hahn, M. A. Ijaz, and W. M. Sample, Phys. Rev. C 2, 1480 (1970).

[6] W.-D. Schmidt-Ott, K. S. Toth, E. Newman, and C. R. Bingham, Phys. Rev. C 10, 296 (1974).

[7] E. Newman, K. S. Toth, D. C. Hensley, and W.-D. Schmidt-Ott, Phys. Rev. C 9, 674 (1974).

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

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

[10] S. Raman and N. B. Gove, Phys. Rev. C 7, 1995 (1973).

[11] M. D. Devous, Sr., and T. T. Sugihara, J. Inorg. Nucl. Chem. 36, 1697 (1974).

[12] K. S. Toth, C. R. Bingham, and W.-D. Schmidt-Ott, Phys. Rev. C 10, 2550 (1974).

[13] W. W. Bowman, T. T. Sugihara, and F. R. Hammiter, Phys. Rev. C 3, 1275 (1971).

[14] D. R. Haenni, T. T. Sugihara, and W. W. Bowman, Phys. Rev. C 5, 1113 (1972).

[15] D. G. Burke, G. Løvhøiden, and J. C. Waddington, Phys. Lett. 43B, 470 (1973).

[16] R. Arlt, G. Beyer, V. V. Kuznetsov, V. Neubert, A. V. Potempa, U. Hagemann, and E. Herrmann, Dubna Report No. P6-5681 (unpublished).

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

[18] C. Ekstroem, S. Ingelman, M. Olsmats, and B. Wannberg, Phys. Scr. 6, 181 (1972).

[19] Ts. Vylov, K. Ya. Gromov, I. I. Gromova, G. I. Iskhakov, V. V. Kuznetsov, M. Ya. Kuznetsova, N. A. Lebedev, and M. I. Fominikh, Izv. Akad. Nauk SSSR, Ser. Fiz. 36, 2124 (1972) [Bull. Acad. Sci. USSR—Phys. Ser. 36, 1864 (1972)].

[20] G. Jansen, H. Morinaga, and C. Signorini, Nucl. Phys. A128, 247 (1969).