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Brief Reports

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Single-proton states in ^{147}Tb

K.S. Toth, D.M. Moltz, and Y.A. Ellis-Akovali
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

C.R. Bingham
University of Tennessee, Knoxville, Tennessee 37916
and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

M.D. Cable, R.F. Parry, and J.M. Wouters
Lawrence Berkeley Laboratory, Berkeley, California 94720

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With the aid of an on-line isotope separator the decay of ^{147}Dy to levels in ^{147}Tb was investigated in a series of heavy-ion bombardments of rare earth targets. These data allow us to identify the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ proton orbitals in ^{147}Tb, a nucleus with one proton beyond the $^{146}_{64}$Gd$_{82}$ core.

[RADIOACTIVITY ^{147}Dy, measured E_γ, I_γ, $\gamma\gamma$ coinc; ^{147}Tb deduced levels, J^π.]

There is a growing body of evidence for the existence of an energy gap at $Z=64$, after the $g_{7/2}$ and $d_{5/2}$ proton orbitals have been filled. This gap was initially proposed on the basis of α-decay studies. First, in the rare-earth region a plot of Q_α vs N revealed (for example, see Ref. 1) a discontinuity at $Z=64$ indicating an increased stability for that proton configuration. Second, α-decay reduced widths for $N=84$ isotones were shown[2] to reach a minimum at ^{148}Gd, once again suggesting a closure at $Z=64$. More recently, in-beam γ-ray studies[3,4] have found ^{146}Gd to be an unusual even-even nucleus in that it has a 3^- first-excited state. This feature places it in a class of other exceptional nuclei, such as ^{16}0, ^{40}Ca, and ^{208}Pb, and indicates that 82 neutrons and 64 protons represent a doubly closed-shell structure. Because of this, nuclei near ^{146}Gd are of interest.

One nucleus, ^{147}Tb, is especially interesting since its low-lying states should be describable in terms of a proton added to the ^{146}Gd core. They should provide us with information about the underlying spherical proton structure in an isotope located almost halfway between two major proton shells. Up to now, however, the only available low-excitation information[5,6] is that ^{147}Tb has two isomers: a 1.9-min, high spin, probably $h_{11/2}$ state and a 1.6-h, low-spin state whose assignment has been assumed to be $d_{5/2}$. (High-spin states built on the $h_{11/2}$ level, with excitations above 1.2 MeV, have been investigated[7] in beam.) The $\frac{5}{2}^+$ assignment was based on considerations[5,6] of the level's decay properties and spins of neighboring nuclei. However, the ground state spin of ^{151}Tb has been measured[8] to be $\frac{1}{2}$ and a recent study[9] of the decay of the ^{149}Tb 4.1-h level concludes that its assignment is $\frac{1}{2}^+$ rather than $\frac{5}{2}^+$. In addition, the α-decay rates of the low-spin isomers in ^{151,153}Ho (Ref. 10) and in ^{149,151}Tb (Ref. 11) indicate that the low-spin species in ^{147,149,151}Tb have the same spins and parities. Thus, there is reason to believe that the low-spin isomer in ^{147}Tb is $\frac{1}{2}^+$ rather than $\frac{5}{2}^+$.

Besides in-beam γ-ray studies, one way to investigate ^{147}Tb is via the decay of ^{147}Dy. The high-spin, $h_{11/2}$ neutron state in ^{147}Dy was identified[12] with the use of a He gas-jet transport system in a series of ^{14}N + ^{141}Pr irradiations at the Oak

Ridge isochronous cyclotron (ORIC). This state at 750.7 keV deexcites to the $s_{1/2}$ ground state by emitting 678.7-keV *M*4 and 72.0-keV *M*1 transitions through an intermediate $d_{3/2}$ level at 72.0 keV. It also presumably β decays to the ^{147}Tb $h_{11/2}$ level; however, transitions in ^{147}Tb from neither the 750.7-keV level nor the ground state could be identified[12] because of the complexity of the γ-ray spectra observed.

To aid in the identification, we investigated the γ-ray decay properties of ^{147}Dy by producing it in the ^{142}Nd(^{12}C,7*n*) reaction at an incident energy of ~ 127 MeV and mass analyzing it with the on-line mass separator RAMA at the Lawrence Berkeley Laboratory 88-inch cyclotron. Because of the low overall efficiency[13] of the RAMA system for rare earth elements (~ 0.1%) and the relatively small reaction cross section, counting statistics were poor. This was further aggravated by the high γ-ray background near the focal plane of the separator, where the radioactive samples had to be collected and assayed. Nevertheless, in addition to the background γ-ray peaks seen at both masses 148 and 149, we were able to observe at $A = 147$ the 678.7-keV ^{147}Dy^m γ ray, transitions from 1.9-min ^{147}Tb (Refs. 5,6) and three new γ rays of 100.7, 253.4, and 365.3 keV. The energies of the 100.7- and 253.4-keV γ rays are essentially the same as those of two intense transitions seen in ^{149}Dy decay.[14] The correspondence in energy (and atomic number) explains much of the difficulty we had encountered in our gas-jet experiments.[12] These had been done at a ^{14}N incident energy of ~ 142 MeV, i.e., at about the peak of the ^{141}Pr(^{14}N,8*n*) excitation function. However, because of the much larger (^{14}N,6*n*) reaction cross section the amount of ^{149}Dy produced at this energy was still sufficient to cause complications.

To reduce the interference due to ^{149}Dy we made new singles and coincidence γ-ray measurements at ~ 157 MeV, once again utilizing a gas-jet system at the ORIC. Figure 1 shows the spectra observed in coincidence with the three newly identified $A = 147$ γ rays; it is evident that they are in cascade with one another. There is also a peak at ~ 106 keV in Figs. 1(a) and 1(b), which is due to the 106.3-keV γ ray[14] in coincidence with the 100.8- and 253.4-keV ^{149}Dy transitions. By comparing the 106-keV intensities in Figs. 1(a) and 1(b) with those in ^{149}Dy coincidence measurements,[14] we estimate that ~ 12% of the 100.7-keV and ~ 6% of the 253.4-keV γ-ray intensities are due to ^{149}Dy. The *K* x rays seen in Fig. 1 are terbium x rays.

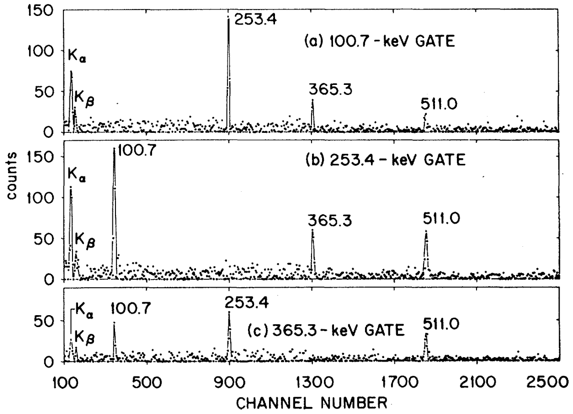

FIG. 1. Gamma-ray spectra observed in coincidence with the 100.7-, 253.4-, and 365.3-keV transitions assigned to the decay of ^{147}Dy^g.

This information and the fact that the three transitions decay with an 80-sec half-life mean that they do not follow ^{147}Dy^m, 59-sec and ^{147}Tb, 1.9-min, decay but rather are transitions from ^{147}Dy^g. In the heavy-ion reactions used the high-spin isomer is produced with the much larger cross section, so that the bulk of ^{147}Dy^g originates from ^{147}Dy^m isomeric decay and the observed 80-sec half-life is the result of a second order, parent-daughter, decay curve.

Before discussing levels in ^{147}Tb (see Fig. 2) we should note that dysprosium *K* x rays in our spectra cannot be due to electron-capture decay; instead, they arise from the internal conversion of the ^{147}Dy^m (primarily the 72.0-keV) transitions. It was therefore possible to deduce the *K*-shell conversion coefficient for the 72.0-keV transition from its intensity and the *K* x-ray intensity in the spectrum gated by the 678.7-keV γ ray. The coefficient was found to be 5.2 ± 0.5, so that the 72.0-keV γ ray is mainly *M*1 with an *E*2 admixture of

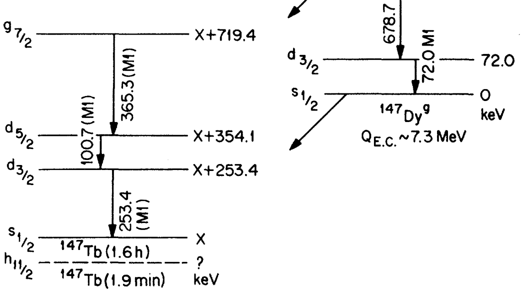

FIG. 2. Decay of ^{147}Dy to levels in ^{147}Tb.

about 4%,[15] as expected for a transition connecting $d_{3/2}$ and $s_{1/2}$ levels (Fig. 2).

In ^{145}Eu the lowest five levels[16] are represented by the $d_{5/2}$, $g_{7/2}$, $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$ proton orbitals. These ^{145}Eu states are below 1.05 MeV with the level-energy trend[16] indicating further compression in ^{147}Tb. The cascading 100.7-, 253.4-, and 365.3-keV transitions associated with ^{147}Dy^g decay must connect four of these levels. They must be the positive parity orbitals because the three γ rays are in prompt coincidence. The transitions are placed in the cascade (see Fig. 2) based on relative photon intensities, 253.4 keV (100), 100.7 keV (24 $\pm$ 5), and 365.3 keV (26 $\pm$ 5), and on the fact that the transitions should be mainly $M1$ with a small $E2$ admixture. When conversion is taken into account the following total intensities are obtained: 253.4 keV (100), 100.7 keV (65 $\pm$ 14), and 365.3 keV (25 $\pm$ 5). From the γ-ray decay pattern (no cross-over transitions are observed) and the short half-lives of the excited states, we conclude that the spin sequence of these four levels must be monotonic. A $g_{7/2}$ assignment for the 1.6-h level is ruled out because the $M2$ transition then expected between the $\frac{7}{2}^+$ and $\frac{11}{2}^-$ states is not compatible with the half-lives of either the 1.6-h or the 1.9-min isomers. Thus the 1.6-h level is the $s_{1/2}$ state and the level sequence is $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+ \rightarrow \frac{3}{2}^+ \rightarrow \frac{1}{2}^+$. The electron-capture decay of the 1.6-h isomer needs to be reexamined in the light of the information we have obtained.

The $\frac{7}{2}^+$ state cannot be fed directly from the $\frac{1}{2}^+$ ^{147}Dy ground state. It must therefore be populated by transitions from higher-lying ^{147}Tb levels which are fed by either ^{147}Dy^g or ^{147}Dy^m decay. This feeding to the $\frac{7}{2}^+$ level is apparently fragmented because we were unable to observe any other ^{147}Tb γ rays in our singles and coincidence spectra.

The level order in ^{147}Tb is very different from those in odd-Z $N=82$ nuclei with $Z \leq 63$, where the $g_{7/2}$ and $d_{5/2}$ orbitals are below the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ states. One must remember, however, that the $g_{7/2}$ orbital is a hole state for $Z \geq 59$ and that the $d_{5/2}$ orbital becomes a hole state in ^{147}Tb. With this in mind, we show in Fig. 3 the systematics of single proton levels for $N=82$ nuclei. Hole states are indicated as having negative energies and the ^{147}Tb $s_{1/2}$ orbital is shown as being at zero excitation. One then sees that the ^{147}Tb levels are not discontinuous with respect to the energies of the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ orbitals in the lower-Z isotones. The indication is that the two hole states are more tightly bound in ^{147}Tb, but to understand fully the influence of the $Z=64$ gap on the quasiparticle energies the investigation should be extended to ^{149}Ho. We have not shown the ^{147}Tb $h_{11/2}$ state in Fig. 3. However, from ^{137}Cs to ^{145}Eu this orbital lies below the $d_{3/2}$ and $s_{1/2}$ states, with all three levels dropping by similar amounts of energy as Z increases. Also, the $h_{11/2}$ state in ^{151}Tb is at 99.6 keV,[17] while α-decay studies (see, e.g., Ref. 11) indicate this state to be at ~ 40 keV in ^{149}Tb. For these reasons the $h_{11/2}$ orbital is expected in ^{147}Tb to be low in excitation, close to the $s_{1/2}$ orbital (it is arbitrarily shown in Fig. 2 below the $\frac{1}{2}^+$ level).

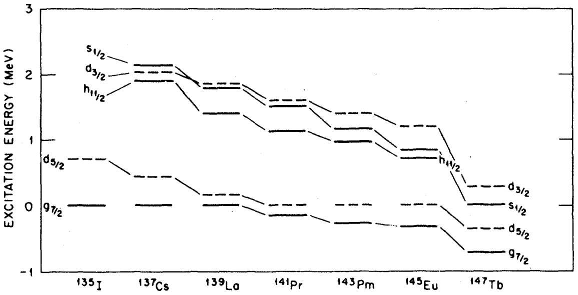

FIG. 3. Energy systematics of single-proton states in odd-Z $N=82$ isotones from ^{135}I to ^{147}Tb.

We compare our results in Table I with level energies calculated by Chasman.[18] In his calculations two types of pairing forces were used: a conventional one and a state dependent one. The energies calculated by using the conventional pairing force are more consistent with our ^{147}Tb level scheme. This set predicts the $s_{1/2}$ level to be the lowest positive parity state, reproduces the experimental level

TABLE I. Calculated and observed level energies (MeV) in ^{147}Tb.

	Calculation[a]		Experiment
$\frac{11}{2}^-$	0.03	0.00	?
$\frac{1}{2}^+$	0.08	0.11	×
$\frac{3}{2}^+$	0.29	0.30	$x+0.253$
$\frac{5}{2}^+$	0.00	0.27	$x+0.354$
$\frac{7}{2}^+$	0.36	0.63	$x+0.719$

[a] Energies are taken from Ref. 18. Values in the left- and right-hand columns were calculated by using a state dependent and a conventional pairing force, respectively.

sequence if the order of the close-lying $d_{3/2}$ (0.30 MeV) and $d_{5/2}$ (0.27 MeV) orbitals is reversed, and places the $g_{7/2}$ state at a relatively high excitation energy. Chasman,[18] contrastingly, concluded on the basis of available information[5,6] that the state dependent pairing force predicted a more accurate level sequence. Finally, we note that, in agreement with the discussion in the previous paragraph, both sets of calculations locate the $h_{11/2}$ orbital at a very low excitation energy in ^{147}Tb.

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