Identification of the $s_{1/2}$ ^{145}Dy ground state

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The electron capture and β^+-decay properties of ^{145}Dy (produced in ^{58}Ni + ^{92}Mo irradiations) were investigated following mass separation of $A=145$ isobars. A new 6(2)-*s* activity was identified and assigned to the $\nu s_{1/2}$ ^{145}Dy ground state. Its decay to low-spin levels in ^{145}Tb indicates that the base state for low-spin levels in this $N=80$ odd-Z nucleus is probably $\pi d_{3/2}$ rather than $\pi s_{1/2}$, as is the case for terbium nuclei with $N=82$, 84, and 86.

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The radionuclide ^{145}Dy is a known [1,2] β-delayed proton precursor. However, little information is available concerning levels in its [electron capture (EC) $+\beta^+$]-decay daughter, ^{145}Tb, with only four γ rays having been observed [3] to follow ^{145}Dy decay. We have investigated $A=145$ isobars with the use of the OASIS on-line-separator facility [4] following their production in ^{58}Ni irradiations of ^{92}Mo. Earlier, we reported [5] on the decay of ^{145}Er and ^{145}Ho. Here we discuss the identification of the ^{145}Dy ground state and the characterization of low-lying single-proton ^{145}Tb levels.

Molybdenum foils, 2.98 mg/cm^2 thick and enriched to 97.37% in ^{92}Mo, were bombarded with 283-MeV ^{58}Ni ions from the Lawrence Berkeley Laboratory SuperHILAC (heavy-ion linear accelerator). Evaporation residues with $A=145$ were mass separated and transported ionoptically to a shielded counting area located 4 m above the separator. There, the radioactive ions were implanted in a fast-cycling tape and transported to a detector array for charged-particle and photon spectroscopy. A ΔE-E particle telescope and a planar hyperpure Ge (HPGe) detector faced the radioactive layer, while a 1-mm-thick plastic scintillator and a 52% Ge detector were located on the opposite side of the collection tape. A second 24% Ge detector was placed at 90° relative to the other detectors, about 45 mm from the radioactive source. Coincidence events registered in the various detectors were recorded in an event-by-event mode, while singles spectra were acquired from all three Ge detectors concurrently. A time-resolved multispectrum mode was used for the singles spectra accumulated in the 52% Ge and HPGe detectors where each tape cycle was divided into eight equal-time intervals for half-life measurements.

Figure 1 displays our delayed-proton data for ^{145}Dy: (a) singles proton spectrum, (b) protons in coincidence with positrons, and (c) γ rays in coincidence with protons. (Note that previous investigators [1,2] have reported only singles information.) In Fig. 1(a) the spectrum is

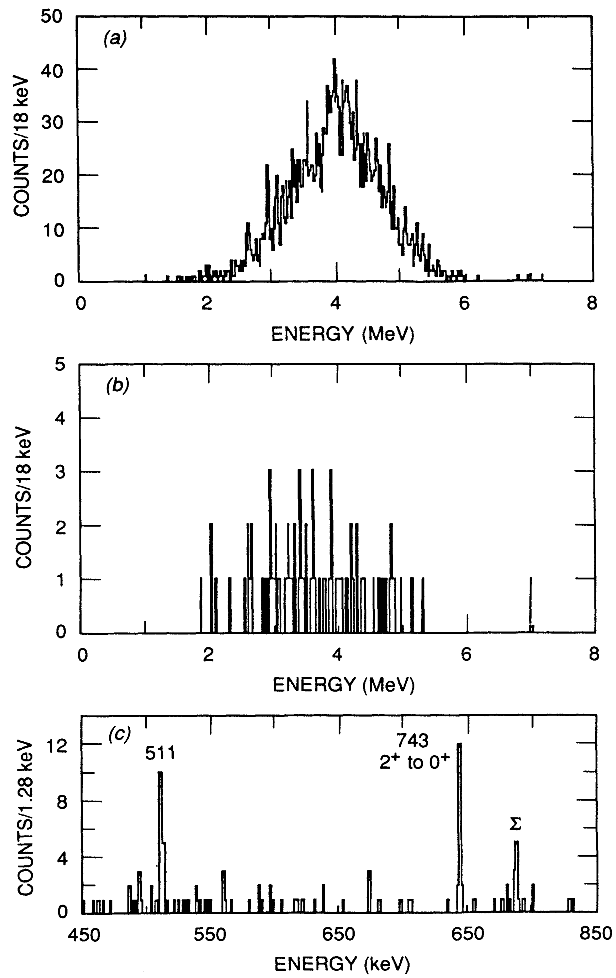

FIG. 1. Delayed-proton data for ^{145}Dy: (a) singles proton spectrum, (b) protons in coincidence with positrons, and (c) ^{144}Gd γ rays in coincidence with protons.

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basically structureless, although there are peaks at about 2.6 and 2.9 MeV (see also Ref. [1]). By requiring positron coincidences one can enhance the fraction of protons emitted from low excitation energies, i.e., from levels found [6] to be associated with the pronounced peaks in the spectra of the $N=81$ precursors, ^{147}Dy, ^{149}Er, and ^{151}Yb. In the case of ^{145}Dy, there are not very many positron-proton coincidences because of the isotope's relatively low Q_{EC} and the high binding energy of the last proton in ^{145}Tb, 7.45 and 1.54 MeV [7], respectively. Despite the poor statistics, it is clear that the spectral centroid is at a lower energy in Fig. 1(b) than in Fig. 1(a); there is also an indication in Fig. 1(b) of an enhancement of the 2.6- and 2.9-MeV peaks relative to the rest of the spectrum.

In Fig. 1(c) one sees a 743-keV γ ray, so that some of the delayed protons feed the first excited 2^+ level in ^{144}Gd located at 743.0 keV. A comparison of the intensity of this coincident γ ray with the total number of observed protons [Fig. 1(a)] tells us that 56% of the protons proceed to the ^{144}Gd ground state with the remainder populating the 2^+ level. This intensity ratio, as we note below, demonstrates that there are states in ^{145}Dy with rather different spins that emit β-delayed protons. On the basis of systematics [5] for odd-A even-Z nuclei in this mass region, the likely levels are the $\nu s_{1/2}$ and $\nu h_{11/2}$ states. Statistical-model calculations predict that 91% of the protons associated with the $s_{1/2}$ state would proceed to the ^{144}Gd ground state, while 71% of the protons from the $h_{11/2}$ level would populate the 2^+ 743.0-keV ^{144}Gd state. From experiment and calculation one then concludes that the $s_{1/2}$ and $h_{11/2}$ ^{145}Dy states each accounts for roughly 50% of the observed protons.

Based on our singles and coincidence γ-ray data, we were able to assign 38 transitions to the decay of ^{145}Dy. Among these transitions, we identified a 108.1-keV γ ray which decays with a 6(2)-s half-life rather than the 14.5(10)-s value that we observed for most of the other intense ^{145}Dy transitions. Because the bulk of the γ-ray decay strength decreases in intensity with the 14.5-s half-life (which agrees with published [3] values for ^{145}Dy), it must represent the decay of the $h_{11/2}$ state (expected to have the much larger production yield in a heavy-ion-induced reaction), while the new 6-s half-life must be due to the decay of the $s_{1/2}$ level.

In nuclei near the 82-neutron shell and beyond the $Z=64$ subshell closure, the three lowest-lying levels are the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ proton states; the $d_{5/2}$ and $g_{7/2}$ proton states lie above them and increase steadily in excitation energy with increasing atomic number. Thus the 6-s 108.1-keV γ ray, associated with the $s_{1/2}$ state in ^{145}Dy, was the likely candidate to be the transition connecting the $s_{1/2}$ and $d_{3/2}$ states in ^{145}Tb. Coincidence spectra shown in Fig. 2 (together with intensity data summarized in Table I) establish the 108.1-keV transition to be at the base of a three γ-ray cascade, $184.5 \rightarrow 145.1 \rightarrow 108.1$ keV. There is also a crossover transition, 253.1 keV, which is coincidence with the 184.5-keV γ ray [Fig. 2(a)] but not with the other two. A sequence of four states 0.0, 108.1, 253.1, and 437.7 keV is then established, and on the basis of single-proton level

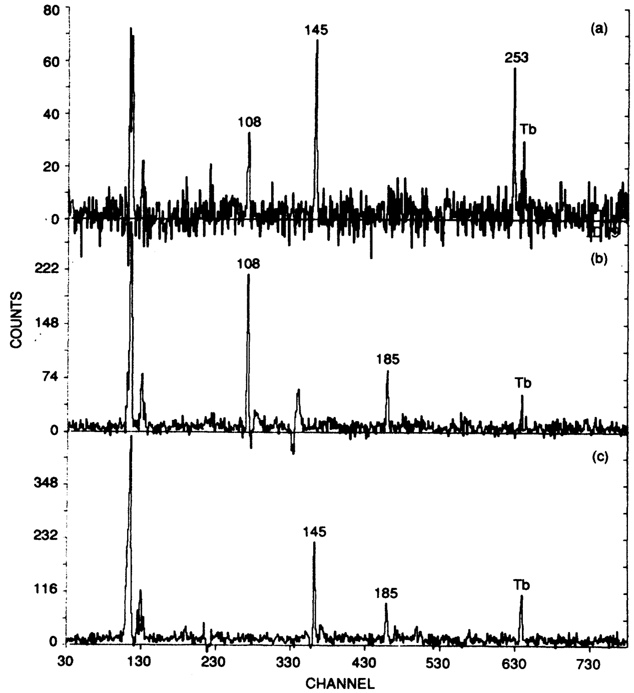

FIG. 2. Gamma-ray spectra observed in coincidence with the following transitions in ^{145}Tb: (a) 184.5 keV, (b) 145.1 keV, and (c) 108.1 keV. Transitions assigned to ^{145}Dy decay are labeled by energy, while the peak labeled as "Tb" belongs to the intense 257.7-keV γ ray which follows ^{145}Tb (EC+β^+) decay.

systematics [8] for $N=82$ and 84 odd-A Tb, Ho, and Tm nuclei, one would propose for them assignments of $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$, respectively. The signature for these states in the $N=82$ and 84 nuclei, as in our case, is the observation of three γ rays (predominantly $M1$ in character) in cascade which connect the $g_{7/2} \rightarrow d_{5/2} \rightarrow d_{3/2} \rightarrow s_{1/2}$ levels. In ^{145}Tb, however, we also observe an intense 437.7-keV γ ray (see Table I), which is not seen in coincidence with any other transition. It thus appears to deexcite the 437.7-keV level directly to the base state (either ground or first excited state) for the ^{145}Tb low-spin levels. The presence of the 437.7- and 253.1-keV crossovers then requires the base state to be $d_{3/2}$ and not $s_{1/2}$ and the level sequence in this $N=80$ nucleus to be $d_{3/2}$, $s_{1/2}$, $d_{5/2}$, and $g_{7/2}$.

This suggested spin sequence is supported by the as-

TABLE I. Energies (E_γ) and relative intensities (I_γ, I_{CE}) for ^{145}Tb transitions associated with the decay of 6-s ^{145}Dy:

E_γ (keV)	I_γ (rel.)	Multipolarity[a]	$I_\gamma + I_{CE}$ (rel.)
108.1(1)	100[b]	(M1)	277
145.1(1)	77(5)	(E2)	130(9)
184.5(1)	45(9)	(M1)	64(13)
253.1(1)	48(9)	(M1)	56(13)
437.7(2)	109(15)	(E2)	111(15)

[a]Assumed multipolarity for I_{CE} determination.
[b]Normalization point for I_γ and I_{CE}.

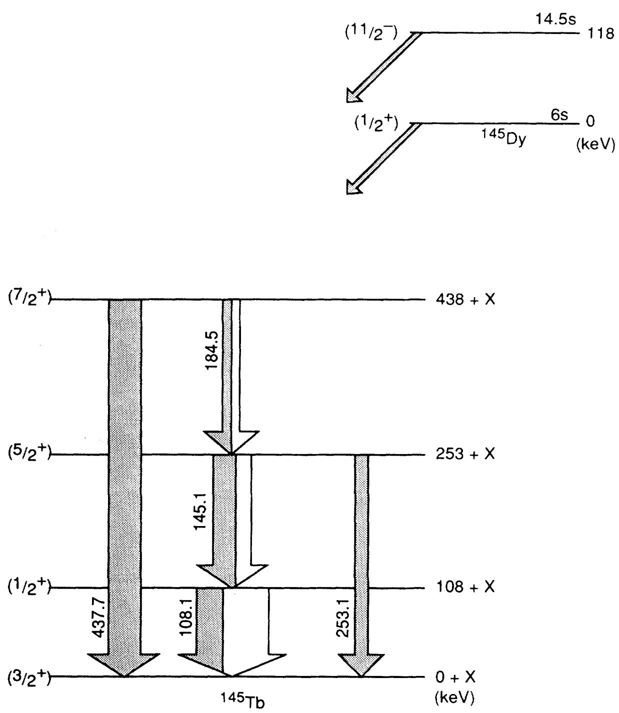

FIG. 3. Partial (EC$+\beta^+$)-decay scheme of ^{145}Dy. We are unable to determine whether the ($3/2^+$) level or the previously known [3] 29.5-s ($11/2^-$) level is the ground state in ^{145}Tb.

signment for the only other known low-spin base state in odd-Z even-N nuclei with $Z \geq 65$ and $N \leq 80$, namely, the direct-proton-emitting isomer in ^{147}Tm which lies $\sim$70 keV above the $h_{11/2}$ ground state. The 360-μs half-life of this isomer, when compared with barrier-penetration half-life calculations for protons originating from various orbitals, has been found (see, e.g., Ref. [9]) to agree much better with a $d_{3/2}$ assignment than with an $s_{1/2}$ assignment.

Figure 3 shows a tentative partial-decay scheme for ^{145}Dy which summarizes the discussion presented in the previous two paragraphs. The 118-keV separation energy between the $h_{11/2}$ and $s_{1/2}$ states in the ^{145}Dy parent is taken from Ref. [5]. We were unable to see any other γ rays in coincidence with the five transitions shown in Fig. 3, so that the feeding to the $g_{7/2}$, $d_{5/2}$, and $s_{1/2}$ levels from higher-lying states (populated directly or indirectly in the decays of the $s_{1/2}$ ground state and $h_{11/2}$ isomer) must be fragmented. Evidence for mixed feedings to the $d_{5/2}$ and $g_{7/2}$ levels from states at higher energies comes from the fact that the half-lives of the four deexciting transitions are intermediate between 6 and 14.5 s, namely, 8(2) s for the 145.1- and 253.1-keV γ rays and 11(3) s for the 184.5- and 437.7-keV γ rays. Also, we have not been able to deduce levels which deexcite to both the $g_{7/2}$ and $h_{11/2}$ (expected to be the base for high-spin levels in ^{145}Tb) proton states. For this reason we cannot establish whether the $d_{3/2}$ or the $h_{11/2}$ level is the ^{145}Tb ground state as we have done [10], for example, in the case of ^{149}Ho states populated in ^{149}Er decay where, based on deexcitations from these linchpin levels, it was determined that the $s_{1/2}$ isomer was 49.0 keV above the $h_{11/2}$ ground state.

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