PHYSICAL REVIEW C VOLUME 39, NUMBER 5 MAY 1989

Identification of ^{145}Er and ^{145}Ho

K. S. Vierinen,* J. M. Nitschke, P. A. Wilmarth, R. M. Chasteler,
A. A. Shihab-Eldin,† and R. B. Firestone
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

K. S. Toth and Y. A. Akovali
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

(Received 9 January 1989)

On-line mass separation and K x-ray coincidences were used to identify the β decays of ^{145}Er and ^{145}Ho. Only β-delayed proton emission was observed for ^{145}Er ($T_{1/2}=0.9\pm0.3$ s), and a total of 16 γ-ray transitions were assigned to the β decay of ^{145}Ho ($T_{1/2}=2.4\pm0.1$ s). A ^{145}Ho decay scheme was constructed which incorporates 13 γ-ray transitions and 10 excited levels in ^{145}Dy and establishes the $\nu h_{11/2}$ isomeric level at $E_x=118.2$ keV. The low-lying neutron-hole structure in ^{145}Dy is compared to level systematics in even-Z nuclei with $N=77$, 79, and 81.

I. INTRODUCTION

The radioactive decays of ^{145}Er and ^{145}Ho were identified at the OASIS (On-line Apparatur for SuperHILAC Isotope Separation) mass separator facility[1,2] online at the Lawrence Berkeley Laboratory's SuperHILAC (heavy-ion linear accelerator). Molybdenum foils, 2.98-mg/cm^2 thick, and enriched to 97.37% in ^{92}Mo, were bombarded with 283-MeV ^{58}Ni ions. This beam energy was selected to optimize the yield of ^{145}Er and ^{145}Ho. Evaporation residues from the $2p3n$ and $3p2n$ reaction channels were mass separated and the $A=145$ isobars were 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 of the tape cycles (1.6, 4, 16, and 40 s) was divided into eight equal time intervals for half-life measurements.

II. RESULTS

A. Decay of $^{145}_{68}$Er$_{77}$

The predicted decay energy, $Q_{\rm EC}$ (where EC stands for electron capture), for ^{145}Er and the proton binding energy, S_p, in ^{145}Ho are 10.3 MeV (Ref. 3) and 0.2 MeV,[3] respectively. For nuclei in the region of $A=120-150$ and $N<82$ with $(Q_{\rm EC}-S_p)\geq 5$ MeV, β-delayed proton emission has been observed almost exclusively from odd-N precursors.[2,4] As expected, ^{145}Er also showed β-delayed proton decay in both the 1.6- and 4-s tape cycles, based on protons observed in coincidence with Holmium K x rays, and with the known[5] $2^+\rightarrow0^+$ and $4^+\rightarrow2^+$ γ-ray transitions in ^{144}Dy. Due to the predicted small cross section of 0.1 mb (Ref. 6) and a half-life of 1.2 s estimated from the gross theory of β decay,[7] the detection of any γ rays associated with the β decay of ^{145}Er was below the sensitivity limits of our system.

The observation of ^{145}Er delayed protons was complicated by the presence of delayed protons from ^{145}Dy.[8] The predicted cross section for the production of ^{145}Dy is about 60 mb (Ref. 6) and, although the energetics for proton emission are much more favorable in ^{145}Er, the observed delayed proton activity at all tape cycle times was predominantly due to ^{145}Dy. In the 16- and 40-s cycle times, a single-component half-life of 8 s was determined for the ^{145}Dy delayed protons. With the ^{145}Dy half-life fixed at 8 s and assuming a negligible contribution from potential ^{145}Ho protons, a two-component analysis of the decay curves associated with the delayed protons in the 1.6- and 4-s tape cycles yielded a half-life of 0.9 ± 0.3 s for ^{145}Er.

B. Decay of $^{145}_{67}$Ho$_{78}$

Sixteen γ-ray transitions were assigned to the decay of ^{145}Ho (see Table I). A half-life of 2.4 ± 0.1 s was deduced from the decay of the Dy K x rays and the strongest γ rays in ^{145}Dy. The gross theory estimate[7] of 2 s is in good agreement with the measured half-life. The predicted energy difference $(Q_{\rm EC}-S_p)=5.5$ MeV (Ref. 3) indicates that β-delayed proton emission is a possible decay mode for ^{145}Ho. However, no proton events coincident with Dy K x rays or ^{144}Tb γ rays were observed. This is similar to other measurements of β-delayed proton emission in this mass region where odd-Z, even-N nuclei are usually weak proton precursors.[2,4] Gamma-ray spectra measured in coincidence with Dy K x rays are shown in Figs. 1(a) and 1(b), while our proposed partial decay scheme

TABLE I. Gamma-ray energies, intensities, and coincidence information for ^{145}Ho β decay.

E_γ (keV)	I_γ (relative)[a,b]	Coincident γ rays[c]
45.2 ± 0.1 (Dy K_{α_2})	68 ± 5[d]	all γ rays in this table
46.0 ± 0.1 (Dy K_{α_1})	120 ± 10[d]	all γ rays in this table
66.3 ± 0.1	15 ± 2	x, 317,334,340,402,(543)
249.2 ± 0.2[e]	~5	x
309.1 ± 0.1	25 ± 2	x,313,402,543
312.9 ± 0.1	95 ± 5	x,309,388,402,543
315.1 ± 0.2[e]	12 ± 2	x,(313)
316.6 ± 0.2[e]	8 ± 2	x
334.1 ± 0.1	90 ± 2	x,66,340,402,543
339.8 ± 0.1	100	x,66,334,402,543
387.6 ± 0.2	15 ± 5	x,313
401.8 ± 0.1	85 ± 5	x,66,309,313,334,340,498,622
498.3 ± 0.2	12 ± 3	x
543.2 ± 0.2	20 ± 5	x,66,309,313,334,340,622
563.3 ± 0.2	15 ± 5	x
622.1 ± 0.2	15 ± 5	x,402
700.5 ± 0.3	20 ± 5	x
852.0 ± 0.5	5 ± 2	x,(334),(402)

[a] Intensities are relative to a value of 100 for the 339.8-keV γ ray.
[b] For absolute intensity per 100 decays of ^{145}Ho, multiply by 0.15.
[c] The notation x means that a coincidence with Dy K x rays was observed.
[d] Includes the x-ray intensity from internal conversion.
[e] Not placed in the decay scheme (Fig. 2).

for ^{145}Ho is shown in Fig. 2. The K conversion coefficient for the 66.3-keV transition was calculated from the Dy K x-ray and the 66.3-keV γ-ray intensities measured in coincidence with the 339.8-keV transition and in coincidence with positrons. A small correction due to other converted transitions coincident with the 340-keV γ ray was made and a fluorescence yield $\omega_K=0.941$ (Ref. 9) for Dy K x rays was assumed. A K conversion coefficient of $\alpha_K=6.5\pm1.0$ was obtained; this value is consistent with an $M1$ multipolarity[10] for the 66.3-keV transition which has a calculated α_K of 6.83.[10]

In determining the absolute β-decay intensity of ^{145}Ho, the intensities from electron capture (EC) and β^+ decay were added together. The EC intensity (I_{EC}) was derived from the Dy K x-ray intensity after correcting for fluorescence yield ω_K,[9] $I_{\mathrm{EC}(K)}/I_{\mathrm{EC(tot)}}$ ratios,[11] and internal conversion (due to the γ transitions in ^{145}Dy),[10] while the β^+ intensity was extracted from the 2.4-s time component of the 511-keV annihilation radiation peak. The 511-keV intensity was taken as the average value from the HPGe detector and the 24% side detector where geometrical summing was minimal. A correction of 7% for annihilation in flight[12] and a 20% correction for the nonlocalized annihilation geometry were included. An intensity of 565 ± 150 for positrons relative to a value of 100 (Table I) for the 339.8-keV γ ray was obtained. An experimental $I_{\mathrm{EC(tot)}}/I_{\beta^+}$ ratio of $0.21^{+0.14}_{-0.06}$ was then deduced from data accumulated during both tape cycles. (The main source of error in the $I_{\mathrm{EC(tot)}}/I_{\beta^+}$ ratio is the uncertainty in the positron intensity.) This ratio is larger than the limit of <0.10 estimated[11] from the proposed partial decay scheme (Fig. 2), indicating that there may be considerable unobserved β feeding to higher lying levels or

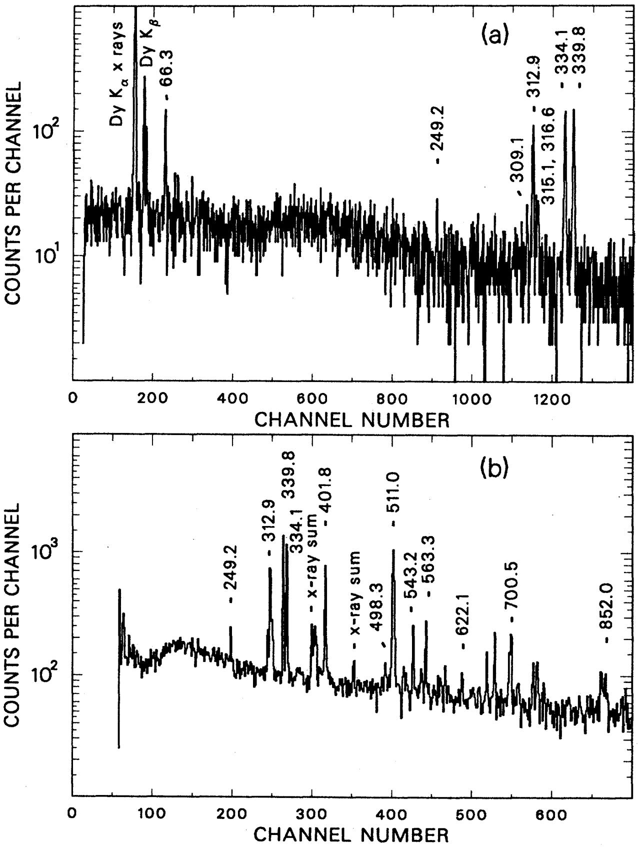

FIG. 1. Gamma-ray spectra observed in the decay of ^{145}Ho as measured with the HPGe detector (a) and 52% Ge detector (b) in coincidence with Dy K x rays. Corresponding background gated spectra were subtracted.

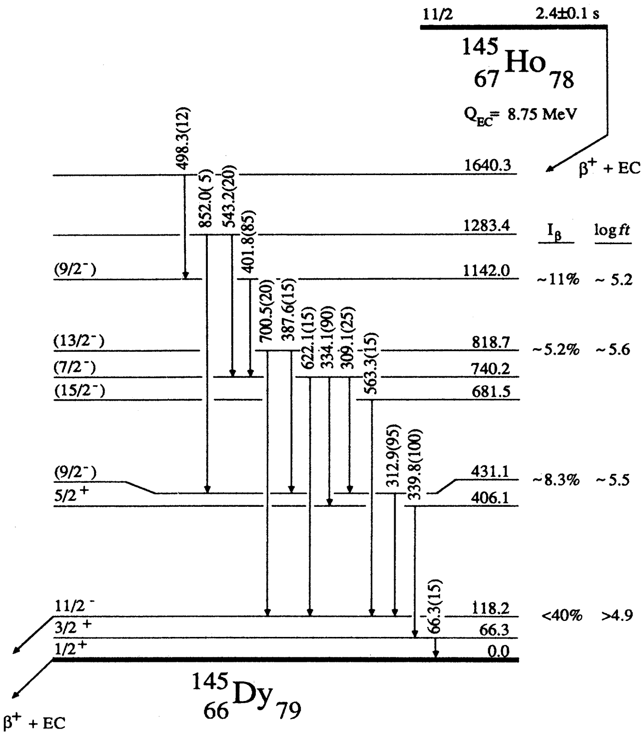

FIG. 2. Partial decay scheme of ^{145}Ho. Intensities are relative to a value of 100 for the 339.8-keV γ ray. Excitation and γ-ray energies are given in keV. The predicted Q_{EC} value is from Ref. 3.

highly converted transitions in ^{145}Dy. However, the large error limits in the predicted Q_{EC} value of 8.75±0.76 MeV (Ref. 3) result in a range of estimated limits of $I_{\mathrm{EC(tot)}}/I_{\beta^+}$ ratios between 0.07 and 0.13.

A log*ft* value of $\sim$5.2 (11% β branching) was calculated[11] for the 1142.0-keV level. This log*ft* value is a lower limit because there may be unobserved γ-ray feeding to this level; nonetheless, based on the uncertainties in the Q_{EC} energy[3] and β branching, error limits of ±0.3 were estimated for this log*ft* value. We suggest a $\nu h_{9/2}$ structure for this state based on our proposed decay scheme and on level systematics of neighboring nuclei. Possible $\nu h_{9/2}$ states have been reported[13] in the $N=79$ isotopes ^{141}Sm and ^{143}Gd at 1063.6 keV and 1250.7 keV, respectively. In the decay scheme (Fig. 2) log*ft* values and β branchings are shown only for those states which are fed by a probable allowed β transition. In the partial decay scheme, only $\sim$43% of the observed β intensity is placed in the decay scheme (no β feeding to the 118.2-keV level was assumed); the missing β intensity most likely feeds the 118.2-keV level and high-lying levels whose γ decay was unobserved. The β intensity to the 118.2-keV level could not be measured directly, but, if an allowed transition with $4.9 < \log ft < 5.5$ is assumed, the calculated β feeding is $\sim$40–10%. Thus $\sim$15–50% of the β intensity feeds high-lying levels, and due to the unknown γ feeding from these levels, the log*ft* values in Fig. 2 have to be considered as lower limits. The 563.3-keV transition is placed between a 681.5-keV level (tentative spin of 15/2$^-$) and the 118.2-keV 11/2$^-$ isomer. This placement is based on high-spin in-beam reaction studies of ^{145}Dy,[5] where this 563.3-keV transition (the most intense γ ray observed) was proposed to feed the lowest 11/2$^-$ level, the excitation energy of which was not known at that time.

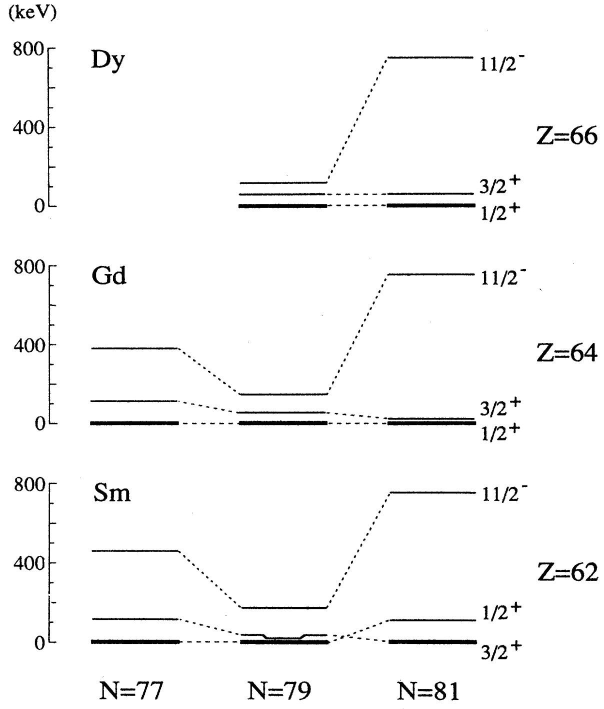

FIG. 3. Level systematics of Sm, Gd, and Dy $N=77$, 79, and 81 nuclei. Only the $\nu s_{1/2}$, $\nu d_{3/2}$, and $\nu h_{11/2}$ neutron-hole levels are shown (no level structure information is available for ^{143}Dy).

The low-lying level structure of ^{145}Dy can be understood in terms of $\nu s_{1/2}$, $\nu d_{3/2}$, $\nu h_{11/2}$, $\nu d_{5/2}$, and $\nu g_{7/2}$ neutron-hole excitations. These orbitals have been observed for most of the known odd-A Ce, Nd, Sm, Gd,

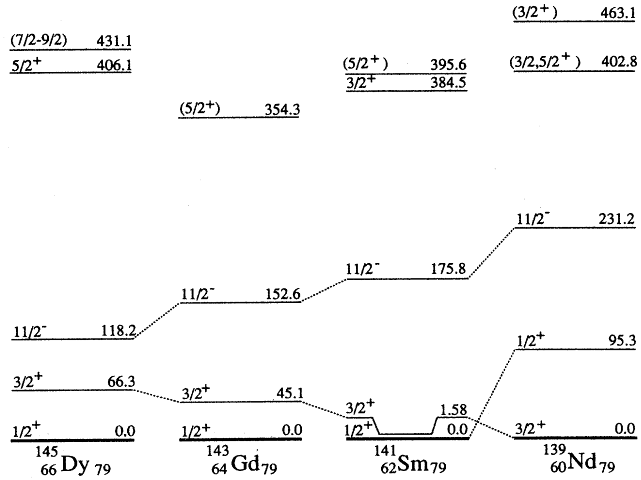

FIG. 4. Low-lying level systematics of neutron deficient even-Z nuclei with $N=79$.

Dy, and Er nuclei,[5,13–18] with $N<82$. Moderate oblate deformation for ^{137}Ce, ^{139}Nd, and ^{145}Dy has been suggested by Goettig *et al.*[5] in their studies of decoupled bands built on the $11/2^-$ levels in some of these odd-A rare-earth nuclei. Using previous information[5,13–18] together with results from our present work, Fig. 3 shows the $\nu s_{1/2}$, $\nu d_{3/2}$, and $\nu h_{11/2}$ neutron-hole excitations plotted as a function of neutron number for the Sm, Gd, and Dy isotopes. An expanded figure with known low-lying neutron-hole levels for the $N=79$ isotones is shown in Fig. 4. In going from $N=81$ to $N=79$ and to $N=77$, the Dy $\nu h_{11/2}$ excitation energy relative to that of the $\nu s_{1/2}$ and $\nu d_{3/2}$ exhibits a behavior similar to that in the Ce, Nd, Sm, and Gd isotopes; it decreases significantly to a minimum at $N=79$, then rises again for $N=77$ (level structure information for ^{143}Dy is not yet available). A minimum for the $\nu h_{11/2}$ level energy is also seen for the same isospin nuclei ^{141}Gd, ^{145}Dy, and ^{149}Er (Figs. 3 and 4), which suggests that Dy isotopes should follow the same trend as Gd and Sm in Fig. 3. It has been suggested by Redon *et al.*[13] that this phenomenon could be understood as a possible change of deformation near $N=79$.

Figure 4 shows that for the $N=79$ nuclei (as is the case for $N=77$ isotones) the relative $\nu h_{11/2}$ level energy decreases systematically from ^{139}Nd to ^{145}Dy, while the $\nu d_{3/2}$ level energy has an opposite trend (Fig. 4). For $N=81$ nuclei between Ce and Er isotopes, the relative $\nu h_{11/2}$ level energy is almost constant at about 750 keV,[14–18] and strong $M4$ γ transitions from the $\nu h_{11/2}$ to the $\nu d_{3/2}$ levels in $Z \geq 66$ nuclei have been observed.[15,17] The corresponding γ transitions are very weak in the $N=77$ and $N=79$ nuclei above $Z=66$ because of the decreasing energy differences between the $\nu h_{11/2}$ and $\nu d_{3/2}$ levels, which may be attributed to the increasing configuration mixing expected when moving away from the $N=82$ closed shell.

ACKNOWLEDGMENTS

We express our thanks to the staff of the SuperHILAC accelerator of the Lawrence Berkeley Laboratory, and to L. F. Archambault and A. A. Wydler for their efficient cooperation. This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The Oak Ridge National Laboratory is operated by Martin Marietta Energy Systems, Inc. for the U.S. Department of Energy under Contract No. DE-AC05-84OR21400.

---

*On leave from University of Helsinki, SF-00170, Finland.

†On leave from Kuwait Institute for Scientific Research, Kuwait.

[1] J. M. Nitschke, Nucl. Instrum. Methods **206**, 341 (1983).

[2] J. M. Nitschke, P. A. Wilmarth, J. Gilat, P. Möller, and K. S. Toth, in *Proceedings of the Fifth International Conference on Nuclei Far from Stability (Rosseau Lake, Ontario, Canada, 1987)*, AIP Conf. Proc. No. 164, edited by I. S. Towner (AIP, New York, 1988), p. 697; J. Gilat, J. M. Nitschke, P. A. Wilmarth, K. Vierinen, and R. B. Firestone, *ibid.*, p. 463.

[3] A. H. Wapstra, G. Audi, and R. Hoekstra, At. Data Nucl. Data Tables **39**, 281 (1988); S. Liran and N. Zeldes, *ibid.* **12**, 101 (1973).

[4] P. A. Wilmarth, Ph.D. thesis, University of California, Berkeley, 1988, Lawrence Berkeley Laboratory Report 26101.

[5] L. Goettig, W. Gelletly, C. J. Lister, R. Moscrop, and B. J. Varley, Nucl. Phys. **A475**, 569 (1987).

[6] W. G. Winn, H. H. Gutbrod, and M. Blann, Nucl. Phys. **A188**, 423 (1972).

[7] K. Takahashi, M. Yamada, and T. Kondoh, At. Data Nucl. Data Tables **12**, 101 (1973).

[8] D. Schardt, P. O. Larsson, R. Kirchner, O. Klepper, V. T. Koslowsky, E. Roeckl, K. Rykaczewski, P. Kleinheinz, and K. Zuber, in *Proceedings of the Seventh International Conference on Atomic Masses and Fundamental Constants, Darmstadt, 1984*, edited by O. Klepper (GSI, Darmstadt, Federal Republic of Germany, 1984), p. 229; K. S. Toth, D. M. Moltz, E. C. Schloemer, M. D. Cable, F. T. Avignone III, and Y. A. Ellis-Akovali, *ibid.*, p. 237.

[9] W. Bambynek, B. Craseman, R. W. Fink, H. U. Freund, H. Mark, C. D. Swift, R. E. Price, and P. V. Rao, Rev. Mod. Phys. **44**, 716 (1972).

[10] F. Rösel, H. M. Fries, K. Alder, and H. C. Pauli, At. Data Nucl. Data Tables **21**, 291 (1978).

[11] N. B. Gove and M. J. Martin, At. Data Nucl. Data Tables **10**, 206 (1971).

[12] G. Azuelos and J. E. Kitching, At. Data Nucl. Data Tables **17**, 103 (1976).

[13] N. Redon, T. Ollivier, R. Beraud, A. Charvet, R. Duffait, A. Emsallem, J. Honkanen, M. Meyer, J. Genevey, A. Gizon, and N. Idrissi, Z. Phys. A **325**, 127 (1986).

[14] E. Nolte, S. Z. Gui, G. Colombo, G. Korschinek, and K. Eskola, Z. Phys. A **306**, 223 (1982).

[15] E. Nolte, in *Proceedings of the International Symposium of Electromagnetic Properties of Nuclei, Tokyo, 1983* (Tokyo Institute of Technology, Tokyo, 1984), p. 129.

[16] D. Schardt, P. O. Larsson, R. Kirchner, O. Klepper, V. T. Koslowsky, E. Roeckl, K. Rykaczewski, K. Zuber, N. Roy, P. Kleinheinz, and J. Blomqvist, in *Proceedings of the Seventh International Conference on Atomic Masses and Fundamental Constants, Darmstadt, 1984*, edited by O. Klepper, (GSI, Darmstadt, Federal Republic of Germany, 1984), p. 222.

[17] K. S. Toth, Y. A. Ellis-Akovali, F. T. Avignone III, R. S. Moore, D. M. Moltz, J. M. Nitschke, P. A. Wilmarth, P. K. Lemmertz, D. C. Sousa, and A. L. Goodman, Phys. Rev. C **32**, 342 (1985).

[18] K. S. Toth, J. Gilat, J. M. Nitschke, P. A. Wilmarth, K. Vierinen, and F. T. Avignone III, Phys. Rev. C **36**, 826 (1987).