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

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## ABSTRACT

On-line mass separation and K x-ray coincidences were used to identify the $\beta$ decays of $^{145}$Er and $^{145}$Ho. Only $\beta$-delayed proton emission was observed for $^{145}$Er ($T_{1/2}$=0.9±0.3 s), and a total of 16 $\gamma$ rays were assigned to the $\beta$ decay of $^{145}$Ho ($T_{1/2}$=2.4±0.1 s). A $^{145}$Ho decay scheme was constructed which incorporates 13 $\gamma$-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 mass separator facility[1,2] on-line at the Lawrence Berkeley Laboratory's SuperHILAC. 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 $\Delta$E-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 8 equal time intervals for half-life measurements.

# II. RESULTS

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

The predicted decay energy, $Q_{EC}$, for $^{145}$Er and the proton binding energy, $S_p$, in $^{145}$Ho are 10.3 MeV[7] and 0.2 MeV,[7] respectively. For nuclei in the region of A=120-150 and N<82 with ($Q_{EC}$-$S_p$)$\geq$ 5 MeV $\beta$-delayed proton emission has been observed almost exclusively from odd-N precursors.[2,8] Continuing this systematic trend, $\beta$-delayed

protons were seen in the 1.6- and 4-s tape cycles in coincidence with Ho K x rays, and with the known[9] $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ $\gamma$-ray transitions in $^{144}$Dy. These coincidences unambiguously identify $^{145}$Er as a $\beta$-delayed proton precursor. Due to the predicted cross section of 0.1 mb[10] and a half-life of 1.2 s estimated from the gross theory of $\beta$-decay,[11] the detection of any $\gamma$ rays associated with the $\beta$ 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.[12] The predicted cross section for the production of $^{145}$Dy is about 60 mb[10] 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-s 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, 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 $\gamma$ rays 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 $\gamma$ rays in $^{145}$Dy. The gross theory estimate[11] of 2 s is in good agreement with the measured half-life. The predicted energy difference ($Q_{EC}$-$S_p$)=5.5 MeV[7] indicates that $\beta$-delayed proton emission is a possible decay mode for $^{145}$Ho. However, no proton events coincident with Dy K x rays or $^{144}$Tb $\gamma$ rays were observed. This agrees with established systematics of $\beta$-delayed proton emission in this mass region where odd-Z, even-N nuclei are usually weak proton precursors.[2,8] 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 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 $\gamma$-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 $\gamma$ ray was made and a fluorescence yield $\omega_K$=0.941[3] for Dy K x rays was assumed. A K conversion coefficient of $\alpha_K$=6.5±1.0 was obtained; this value is consistent with an M1 multipolarity[5] for the 66.3-keV transition.

In determining the absolute $\beta$-decay intensity of $^{145}$Ho, the intensities from electron capture (EC) and $\beta^+$ decay were added together. The EC intensity ($I_{EC}$) was derived from the Dy K x-ray intensity after correcting for fluorescence yield $\omega_K$,[3] $I_{EC(K)}/I_{EC(tot)}$ ratios,[4] and internal conversion (due to the $\gamma$ transitions in $^{145}$Dy),[5] while the $\beta^+$ 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[6] and a 20% correction for the non-localized annihilation geometry were included. An intensity of 565±150 for positrons relative to a value of 100 (Table I) for the 339.8-keV $\gamma$ ray was obtained. An experimental $I_{EC(tot)}/I_{\beta+}$ ratio of $0.21^{+0.14}_{-0.06}$ was then deduced from data accumulated in both tape cycles. (The main source of error in the $I_{EC(tot)}/I_{\beta+}$ ratio is the uncertainty in the positron intensity.) This ratio is larger than the limit of <0.10 estimated[4] from the proposed partial decay scheme (Fig. 2), indicating that there may be considerable unobserved $\beta$ feeding to higher lying levels or highly converted transitions in $^{145}$Dy. However, the large error limits in the predicted $Q_{EC}$ value of 8.75±0.76 MeV,[7] result in a range of estimated limits of $I_{EC(tot)}/I_{\beta+}$ ratios between 0.07 and 0.13.

A logft value of ~5.2 (11% $\beta$ branching) was calculated[4] for the 1142.0-keV level.

This logft value is a lower limit because there may be unobserved $\gamma$-ray feeding to this level, nonetheless, based on the uncertainties in the $Q_{EC}$ energy[7] and $\beta$ branching, error limits of $\pm 0.3$ were estimated for this logft 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 isotones $^{141}$Sm and $^{143}$Gd at 1063.6 keV and 1250.7 keV, respectively. In the decay scheme (Fig. 2) logft values and $\beta$ branchings are shown only for those states which are fed by a probable allowed $\beta$ transition. In the partial decay scheme, only ~43% of the observed $\beta$ intensity is placed in the decay scheme (no $\beta$ feeding to the 118.2-keV level was assumed); the missing $\beta$ intensity most likely feeds the 118.2-keV level and high-lying levels whose $\gamma$ decay was unobserved. The $\beta$ intensity to the 118.2-keV level could not be measured directly, but, if an allowed transition with 4.9<logft<5.5 is assumed, the calculated $\beta$ feeding is ~40-10%. Thus ~15-50% of the $\beta$ intensity feeds high-lying levels and due to the unknown $\gamma$ feeding from these levels, the logft 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,[9] where this 563.3-keV transition (the most intense $\gamma$ ray observed) was proposed to feed the lowest $11/2^-$ level, the excitation energy of which was not known at that time.

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, Dy and Er nuclei,[9,13–16] with N<82. Moderate oblate deformation for $^{137}$Ce, $^{139}$Nd, and $^{145}$Dy has been suggested by Goettig et al.[9] in their studies of decoupled bands built on the $11/2^-$ levels in some of these odd-A rare earth nuclei. Using previous information[9,13–16] 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] and strong M4 $\gamma$ transitions from the $\nu h_{11/2}$ to the $\nu d_{3/2}$ levels in Z$\geq$66 nuclei have been observed.[14,17] The corresponding $\gamma$ 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. Finally, we note that strong $h_{11/2}$ to $h_{9/2}$ spin-flip $\beta$ transitions are observed in the $\beta$ decay of o-e and e-e N=82 nuclei,[18] but in the corresponding N=78 nuclei these spin-flip transitions are much slower,[19] indicating once again a probable increase in configuration mixing for N=78 nuclei.

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

| $E_\gamma$(keV) | $I_\gamma$(relative)[a,b] | Coincident $\gamma$ rays[c] |
|---|---|---|
| 45.2±0.1(Dy $K_{\alpha_2}$) | 68±5[d] | all $\gamma$ rays in this table |
| 46.0±0.1(Dy $K_{\alpha_1}$) | 120±10[d] | all $\gamma$ 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 $\gamma$ 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).

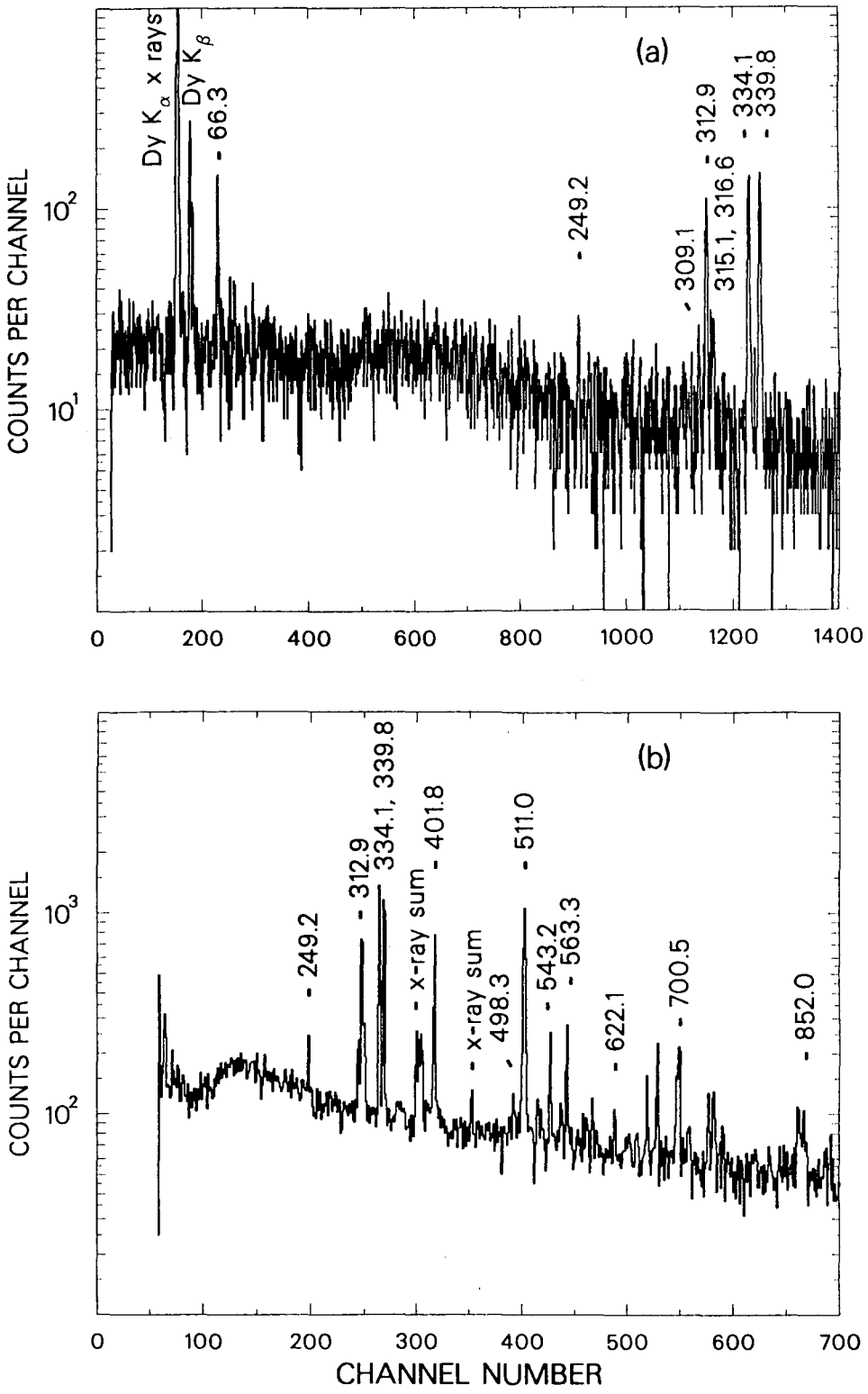


FIG. 1. Gamma-ray spectra associated with the decay of $^{145}$Ho measured with the HPGe detector (a) and 52% Ge detector (b) in coincidence with Dy K x rays. Corresponding background gated spectra were subtracted.

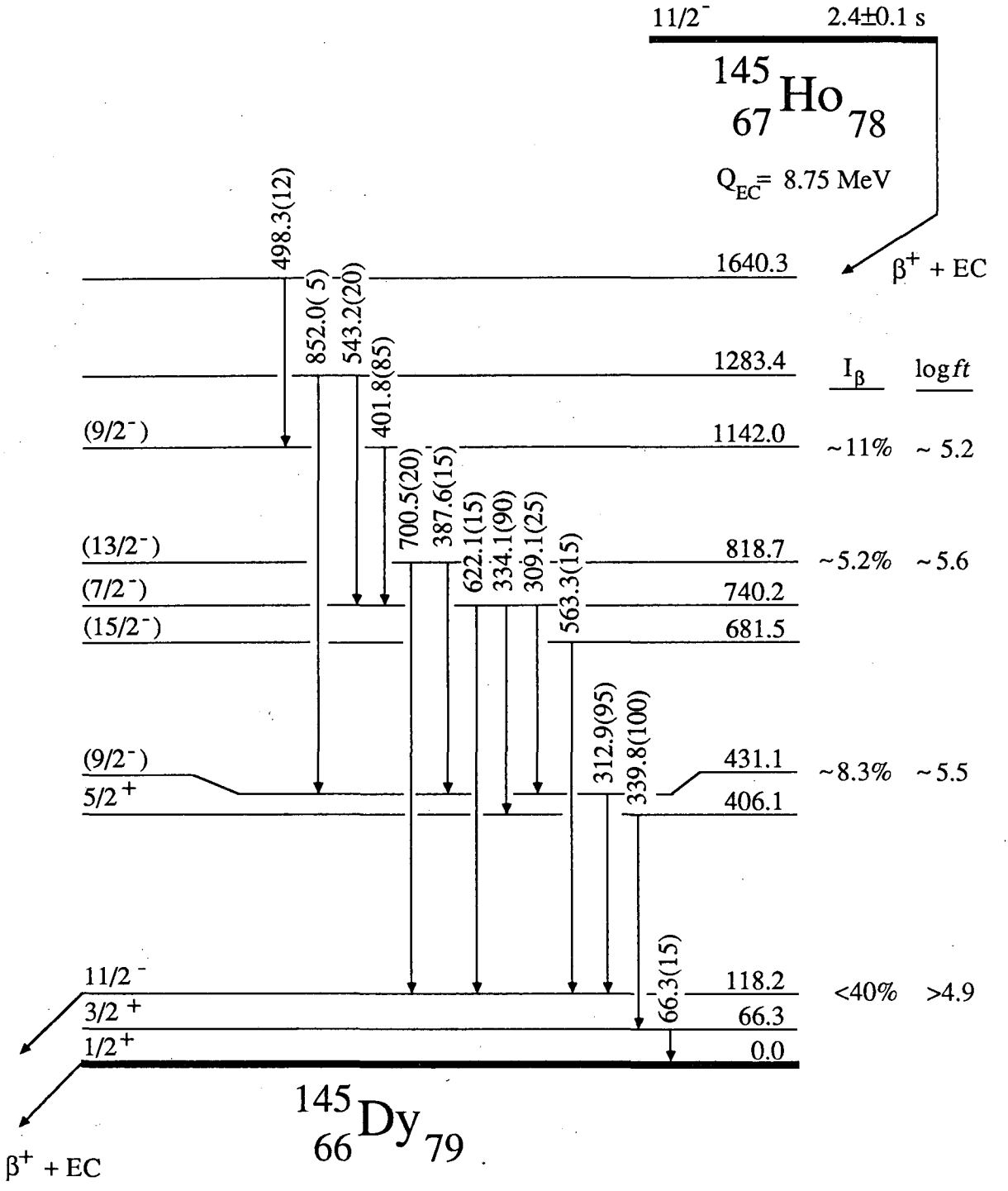


FIG. 2. Partial decay scheme of $^{145}$Ho. Intensities are relative to a value of 100 for the 339.8-keV $\gamma$ ray. Excitation and $\gamma$-ray energies are given in keV. The predicted $Q_{EC}$ value is from Ref. 7.

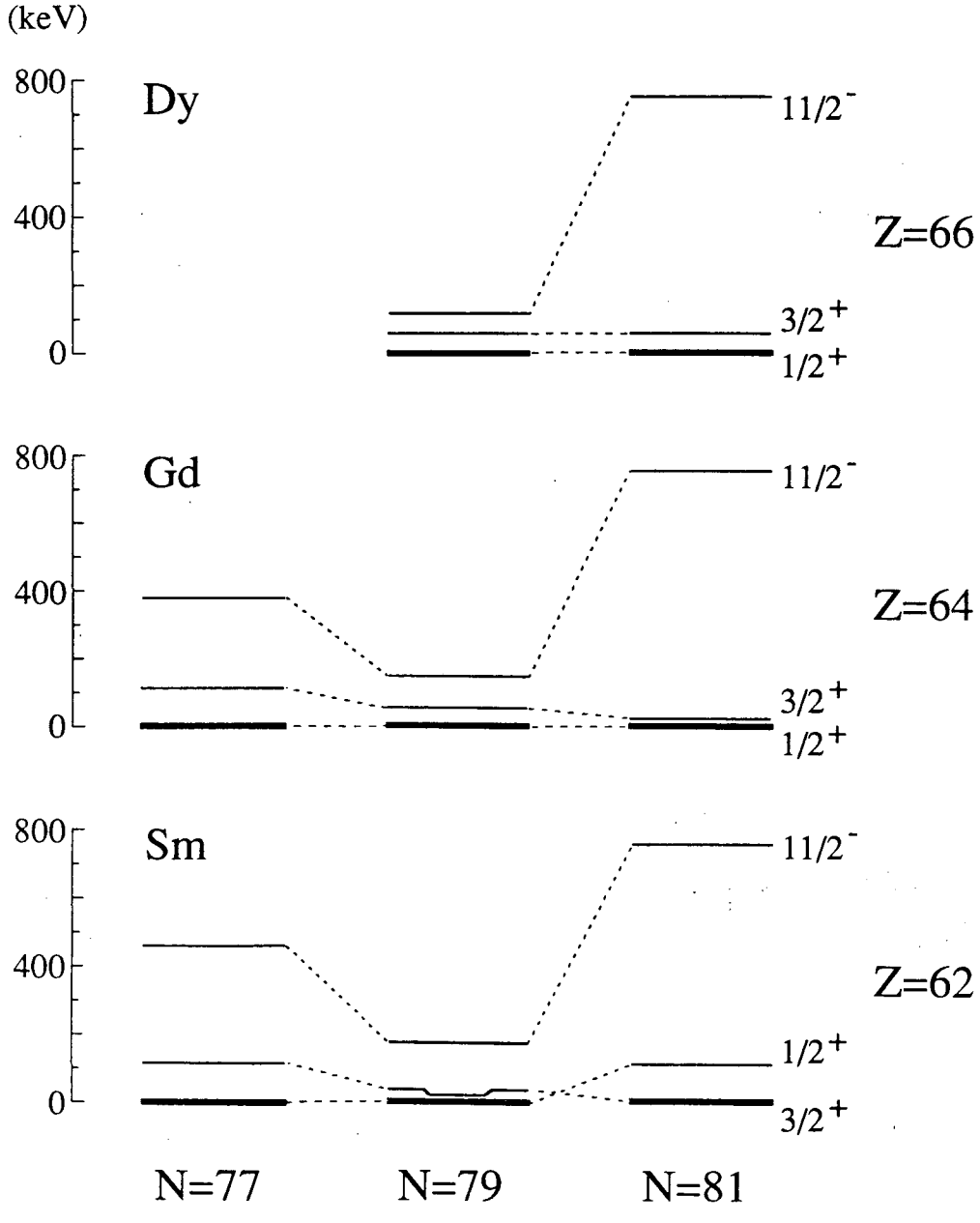


FIG. 3. Level systematics of Sm, Gd, and Dy N=77, 79, and 81 nuclei. Only the $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu h_{11/2}$ neutron hole levels are shown (no level structure information is available for $^{143}$Dy).

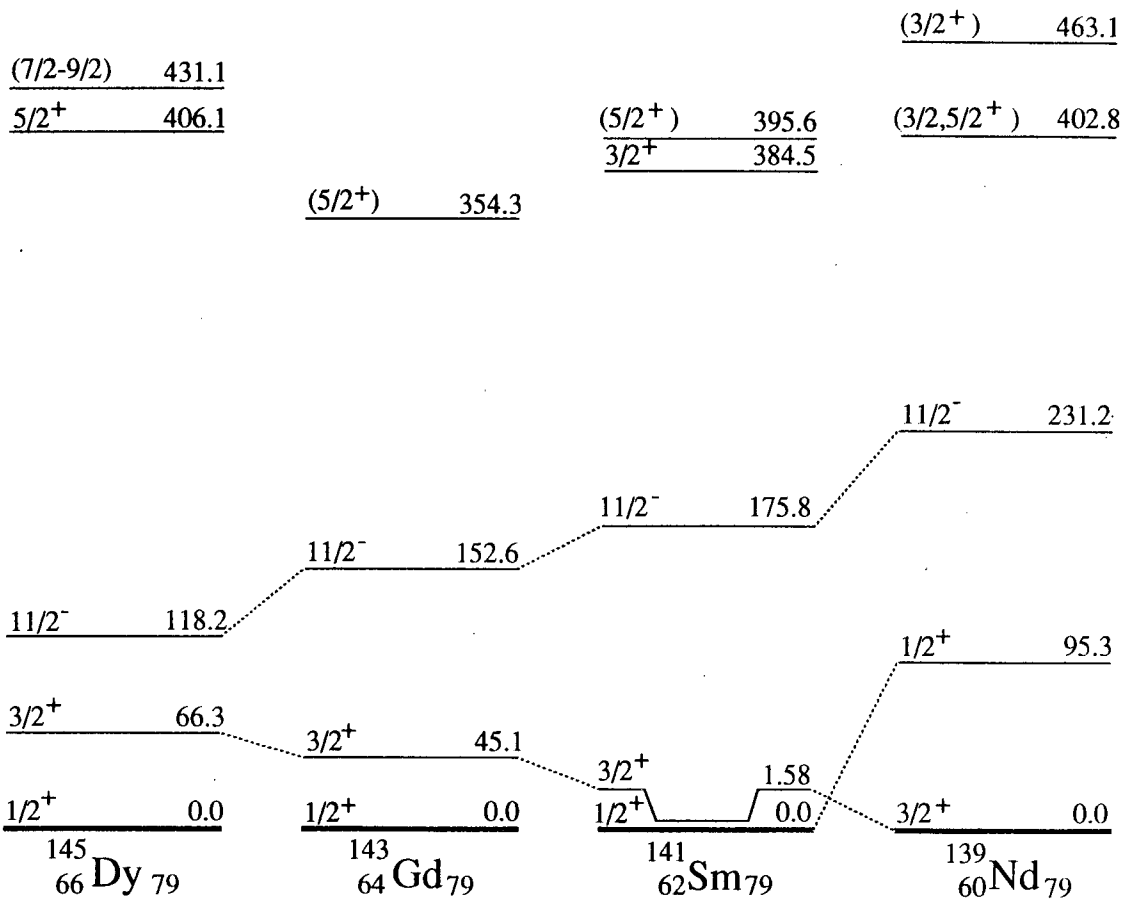


FIG. 4. Low-lying level systematics of neutron deficient even-Z nuclei with N=79.

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