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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 β decays of ^{145}Er and ^{145}Ho. Only β-delayed proton emission was observed for ^{145}Er ($T_{1/2}$=0.9±0.3 s), and a total of 16 γ rays were assigned to the β decay of ^{145}Ho ($T_{1/2}$=2.4±0.1 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 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 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 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 β-delayed proton emission has been observed almost exclusively from odd-N precursors.[2,8] Continuing this systematic trend, β-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 $4^+ \rightarrow 2^+$ γ-ray transitions in ^{144}Dy. These coincidences unambiguously identify ^{145}Er as a β-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 β-decay,[11] 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.[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 γ 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 γ 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 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 agrees with established systematics of β-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 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 ω_K=0.941[3] for Dy K x rays was assumed. A K conversion coefficient of α_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 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,[3] $I_{EC(K)}/I_{EC(tot)}$ ratios,[4] and internal conversion (due to the γ transitions in ^{145}Dy),[5] 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[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 γ 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 β 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% β branching) was calculated[4] for the 1142.0-keV level.

This logft 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[7] and β branching, error limits of ± 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 β branchings are shown only for those states which are fed by a probable allowed β transition. In the partial decay scheme, only ~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 ~40-10%. Thus ~15-50% of the β intensity feeds high-lying levels and due to the unknown γ 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 γ 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 γ 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 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. Finally, we note that strong $h_{11/2}$ to $h_{9/2}$ spin-flip β transitions are observed in the β 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 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).

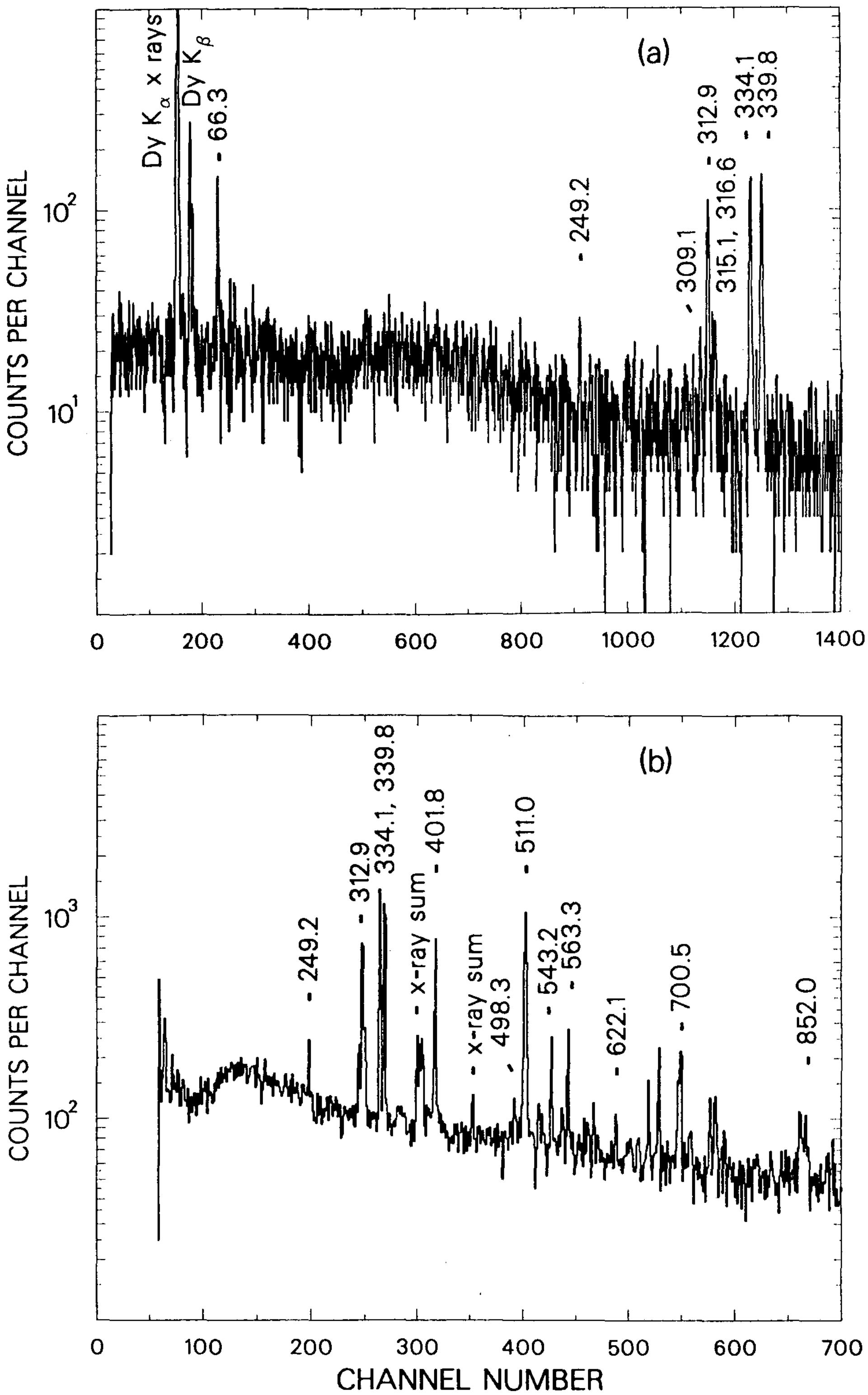

FIG. 1. Gamma-ray spectra associated with the decay of ^{145}Ho measured with the HPGe detector (a) and 52% Ge detector (b) in coincidence with Dy K x rays. Corresponding background gated spectra were subtracted.

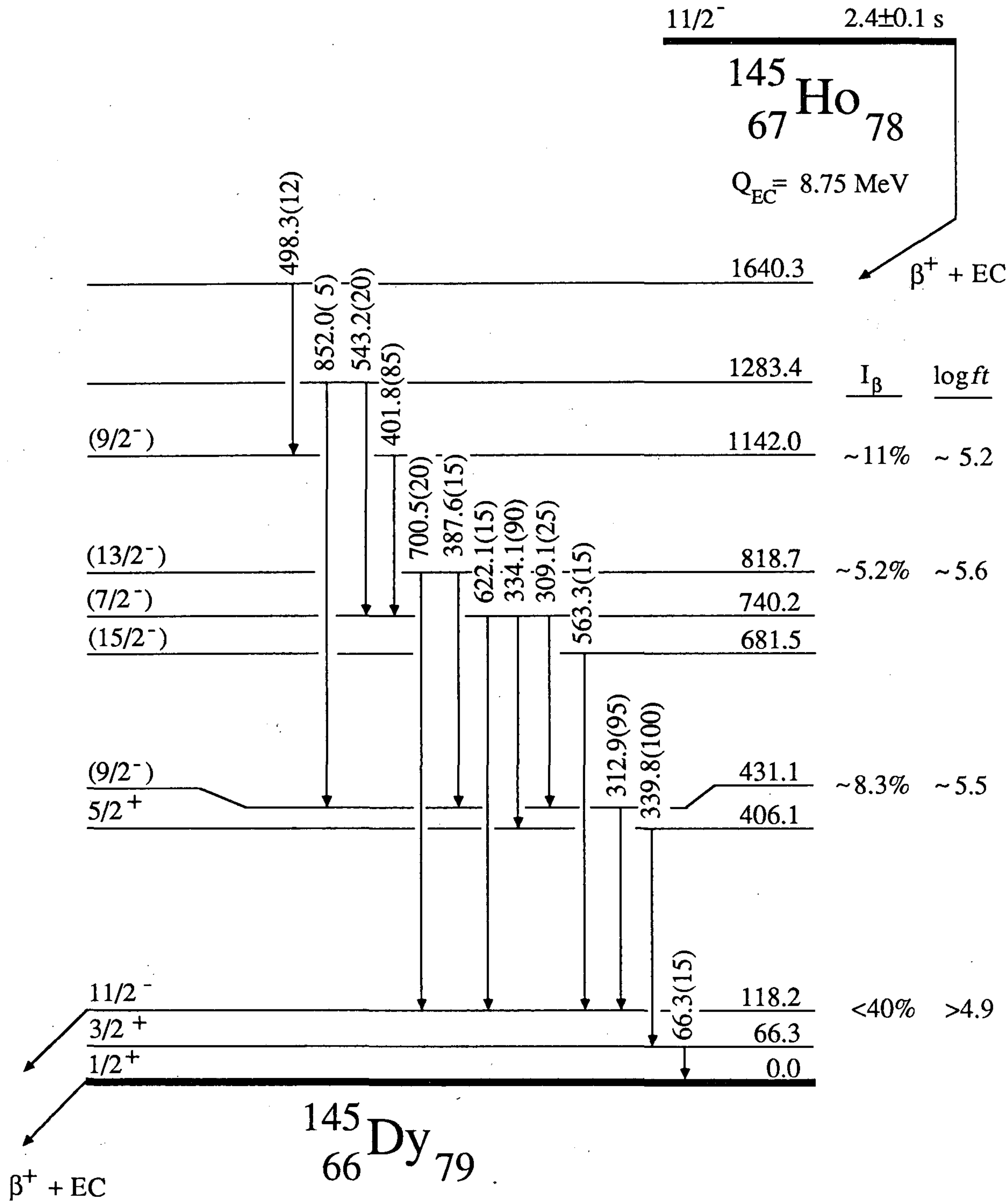

FIG. 2. Partial decay scheme of ^{145}Ho. Intensities are relative to a value of 100 for the 339.8-keV γ ray. Excitation and γ-ray energies are given in keV. The predicted Q_{EC} value is from Ref. 7.

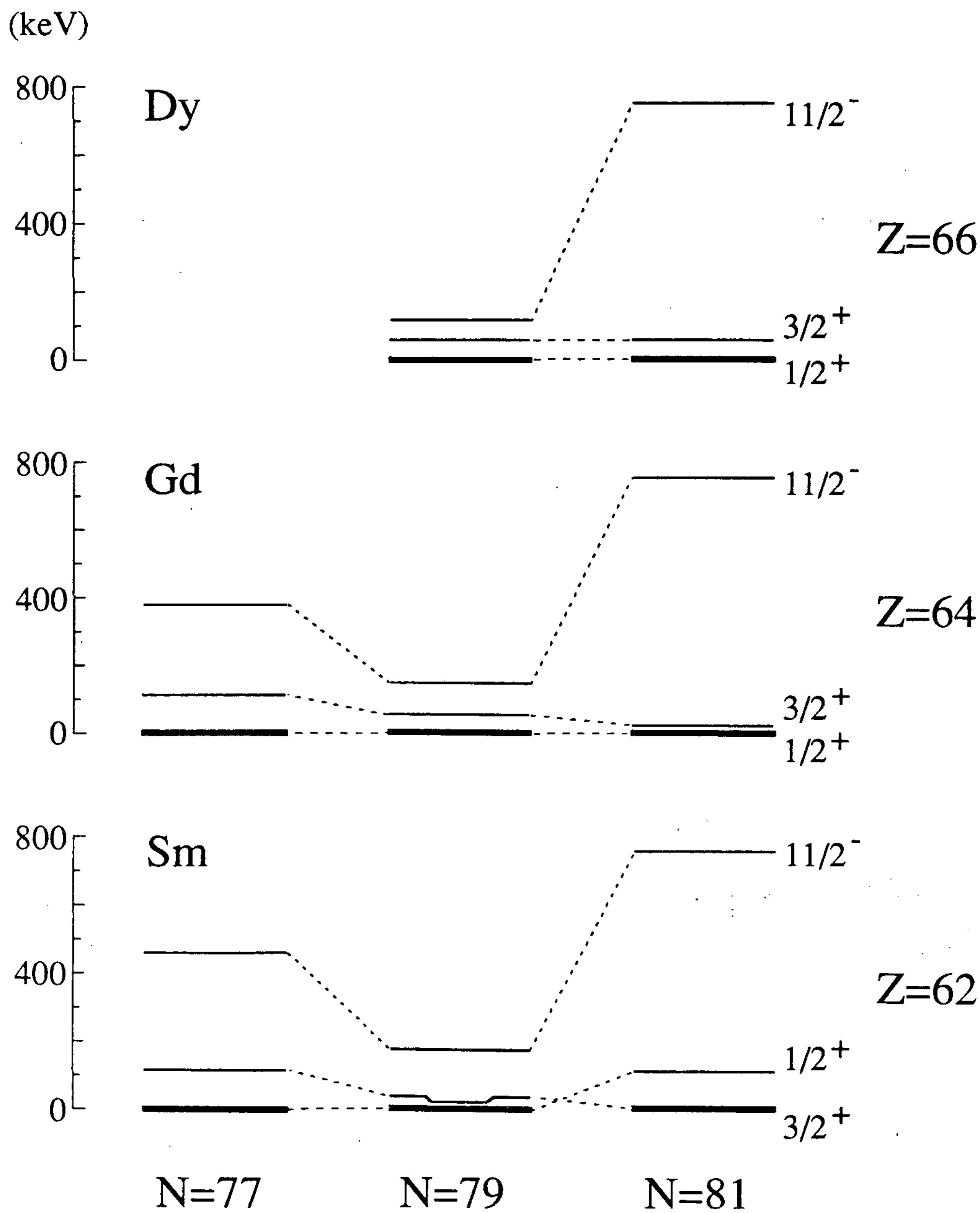

FIG. 3. Level systematics of Sm, Gd, and Dy N=77, 79, and 81 nuclei. Only the $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu h_{11/2}$ neutron hole levels are shown (no level structure information is available for ^{143}Dy).

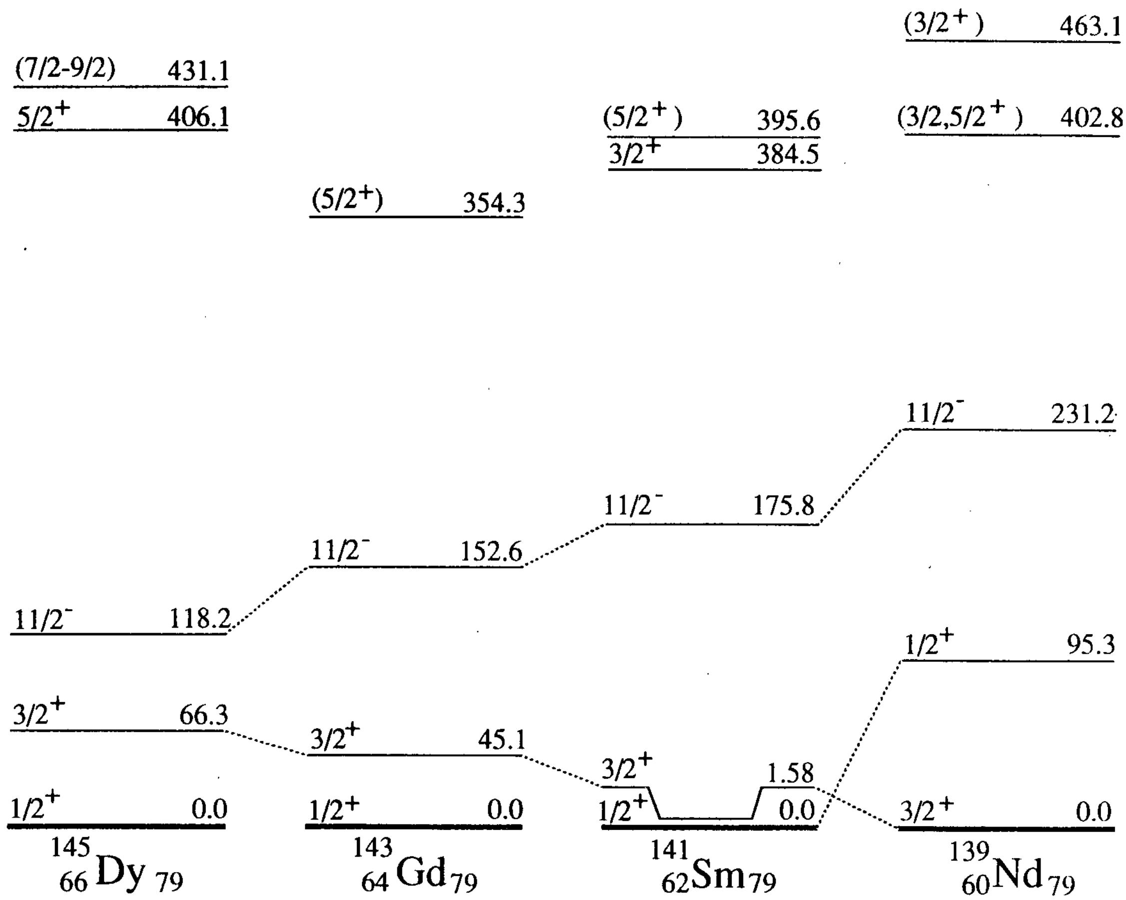

FIG. 4. Low-lying level systematics of neutron deficient even-Z nuclei with N=79.