Four-valence-proton yrast states in $^{150}_{68}Er_{82}$

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(Received 7 March 1984)

The level structure of the four-valence-proton $N=82$ nucleus ^{150}Er has been studied by γ-ray spectroscopy following reactions of 225—255 MeV ^{58,60}Ni beams on ^{92,94,95}Mo and ^{93}Nb targets. Yrast levels in ^{150}Er are established up to 9.5 MeV excitation energy; they include isomeric levels at 2797, 7372, and 9509 keV. The observed levels up to 5222 keV are interpreted in terms of shell model configurations involving the four valence protons outside the ^{146}Gd core. They include states with dominant seniority two and four configurations $\pi h^4_{11/2}$, $\pi h^3_{11/2}s_{1/2}$, and $\pi h^3_{11/2}d_{3/2}$, and octupole excitations. The levels above 5222 keV must involve excitation of the ^{146}Gd core, and they are not interpreted in detail. The energies of the $\pi h^4_{11/2}$ levels are found to agree reasonably with predictions based on empirical two-body interactions taken from the $\pi h^2_{11/2}$ spectrum of ^{148}Dy. Even better agreement is obtained by taking account also of the known $\pi h^3_{11/2}$ energies in ^{149}Ho. The dependence of $E2$ transition probabilities in $N=82$ nuclei on the $\pi h_{11/2}$ subshell occupation number is discussed.

I. INTRODUCTION

The $Z=64$, $N=82$ nucleus ^{146}Gd has many properties of a doubly closed shell system,[1] and the yrast states of neighboring nuclei are well described[2–5] in terms of shell model configurations with a few valence nucleons outside the ^{146}Gd core. Particularly interesting are the proton-rich nuclei with $N=82$. The proton orbitals between $Z=64$ and $Z=82$ are $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$; consequently, $\pi h^n_{11/2}$ excitations are expected to figure prominently in the yrast spectroscopy of $N=82$ nuclei with n valence protons. Using empirical two-body matrix elements obtained from the experimental $\pi h^2_{11/2}$ spectrum[3] of ^{148}Dy, and a value of $1.52e$ for the proton effective charge extracted from the measured $B(E2;10^+\rightarrow 8^+)$ in the same nucleus, Lawson[6] has calculated the energies of the $\pi h^n_{11/2}$ states, and the $E2$ transition probabilities between them, for the $N=82$ nuclei ^{149}Ho, ^{150}Er, ^{151}Tm, and ^{152}Yb, with three to six valence protons outside ^{146}Gd.

The first studies[4] of the three-proton nucleus ^{149}Ho located its $\pi h^3_{11/2}$ yrast states up to a $\frac{27}{2}^-$ isomer at 2737 keV; both the level energies and the $B(E2;27/2^-\rightarrow 23/2^-)$ were found to agree well with the predictions.[6] We have now investigated the four-proton $N=82$ nucleus ^{150}Er, the counterpart in this region of ^{212}Rn, which has four valence protons outside a ^{208}Pb core. The well-studied yrast level scheme[7] of ^{212}Rn is often the chosen showpiece used (a) to illustrate the generation of high angular momentum in nuclei by the successive alignment of the orbital motions of individual nucleons,[8] and (b) to test the predictive power of various calculational approaches.[9] We have already reported briefly[10] on the ^{150}Er level scheme up to a 2.55-μs, 10^+ isomer at 2797 keV, and Nolte *et al.*[11] have given similar results. The levels located are interpreted as $\pi h^4_{11/2}$ seniority-two ($v=2$) states up to $I^\pi=10^+$, a 3^- octupole excitation, and 5^- and 7^- states with dominant $\pi h^3_{11/2}s_{1/2}$ and $\pi h^3_{11/2}d_{3/2}$ configurations, also $v=2$. At higher energies along the yrast line one expects seniority-four excitations involving the valence protons, until the maximally aligned $\pi h^4_{11/2}$ $I^\pi=16^+$ state is reached around 5.5 MeV excitation energy. The continuation of the ^{150}Er yrast line above $I=16$ must then involve the excitation of the ^{146}Gd core. The present paper gives a more complete account of the investigations, which have now established yrast levels in ^{150}Er up to 9.5 MeV.

II. EXPERIMENTAL METHODS AND RESULTS

A. Production and identification of ^{150}Er γ rays

Enriched ^{92,94}Zr, ^{93}Nb, and ^{92,94,95}Mo targets, ~1 mg/cm^2 thick, located at the center of a 33 cm×30 cm NaI sum spectrometer, were bombarded with 225—255 MeV ^{58}Ni and ^{60}Ni beams from the Argonne superconducting linac. Recoiling residual nuclei were stopped in an 11 mg/cm^2 ^{208}Pb catcher foil placed 21 cm downstream. High multiplicity triggering of the sum spectrometer gave both a total energy signal $E_{\rm sum}$ from prompt γ rays, and a timing signal marking the occurrence of a compound nuclear reaction. Measurements of γ rays from products deposited on the catcher foil were performed, typically with one planar and three large coaxial Ge(Li) detectors; such an arrangement is particularly

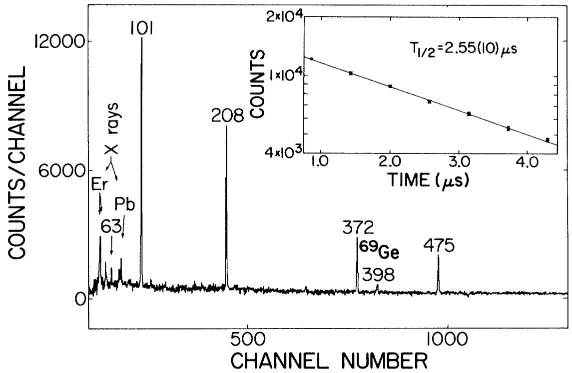

FIG. 1. Off-beam γ-ray spectrum for the reaction 245 MeV $^{60}Ni+^{92}Mo$ measured with the planar detector. The labeled ^{69}Ge γ ray arises from reactions of ^{60}Ni with carbon impurities in the target. The lifetime data are displayed in the inset.

suitable for studying the decay of isomers with half-lives exceeding 10 ns.

The reactions studied here form relatively cold compound nuclei ($E_{ex}<50$ MeV), which deexcite through only a few strong exit channels. Since, however, charged particle evaporation competes favorably with neutron evaporation in this very neutron deficient region, particular care was necessary in making isotopic assignments. The identification of the γ rays associated with a specific residual nucleus was based on the following:

(a) coincidences with characteristic K x rays, which determined the atomic number Z;

(b) coincident sum-spectra, excitation function, and cross-bombardment results, which together settled the A assignment.

Strong 101, 208, 372, 475, and 1579 keV γ rays, all coincident with Er x rays, appeared prominently with the reaction systems $^{60}Ni+^{93}Nb\rightarrow^{153}Tm^*$, $^{60}Ni+^{92}Mo\rightarrow^{152}Yb^*$, and $^{58}Ni+^{95}Mo\rightarrow^{153}Yb^*$; the same γ rays were observed with much weaker intensities in the $^{60}Ni+^{92}Zr\rightarrow^{152}Er^*$ reaction. As described in Ref. 10, the coincident sum spectra and the excitation function results showed that these γ rays followed the emission of two nucleons from the $^{152}Yb^*$ and $^{152}Er^*$ compound nuclei, and three nucleons from $^{153}Tm^*$ and $^{153}Yb^*$, and they are therefore firmly assigned to ^{150}Er. These transitions and a few weaker lines were found (Fig. 1) to follow the decay of an isomeric level at 2797 keV in ^{150}Er with the half-life

$$T_{1/2}(2797\text{ keV})=2.55\pm0.10\ \mu s\ .$$

The γ-ray energies and relative intensities are listed in Table I. We observed many of the same ^{150}Er γ rays in the radioactive decay of ^{150}Tm, and the γ-ray intensities from this decay are also given in Table I, since they were vital in settling the transition ordering.

TABLE I. Energies and relative intensities of ^{150}Er γ rays occurring in the deexcitation of the 2.55 μs isomer. Approximate γ-ray intensities following the β^+/EC decay of ^{150}Tm are also given.

E_γ (keV)	I_γ (2.55 μs decay)	I_γ (^{150}Tm β^+/EC decay)
63.2±0.3	5.8 ±0.9	
100.5±0.1	75 ±5	
112.6±0.3	2.6 ±0.3	
207.6±0.2	101 ±7	96
360.4±0.2	5.2 ±0.9	11
372.4±0.2	101 ±7	14
474.5±0.2	107 ±7	76
1578.8±0.2	100	100
1786.3±0.3	6 ±2	~6

B. The ^{150}Er level structure below the 2.55 μs isomer

Detailed $\gamma\gamma$ coincidence measurements were performed using the reactions $^{93}Nb+255$ MeV $^{60}Ni\rightarrow^{153}Tm^*$ and $^{95}Mo+258$ MeV $^{58}Ni\rightarrow^{153}Yb^*$. Coincidences between the sum spectrometer and two of the Ge detectors were required, and the data were accumulated as multiparameter events, which included γ-ray energies, E_{sum}, $t_{\gamma\gamma}$, and $t_{\gamma\,sum}$. Representative coincidence spectra are shown in Fig. 2. The five strong ^{150}Er γ rays were found to be in cascade, preceded by a highly converted 63.2-keV transi-

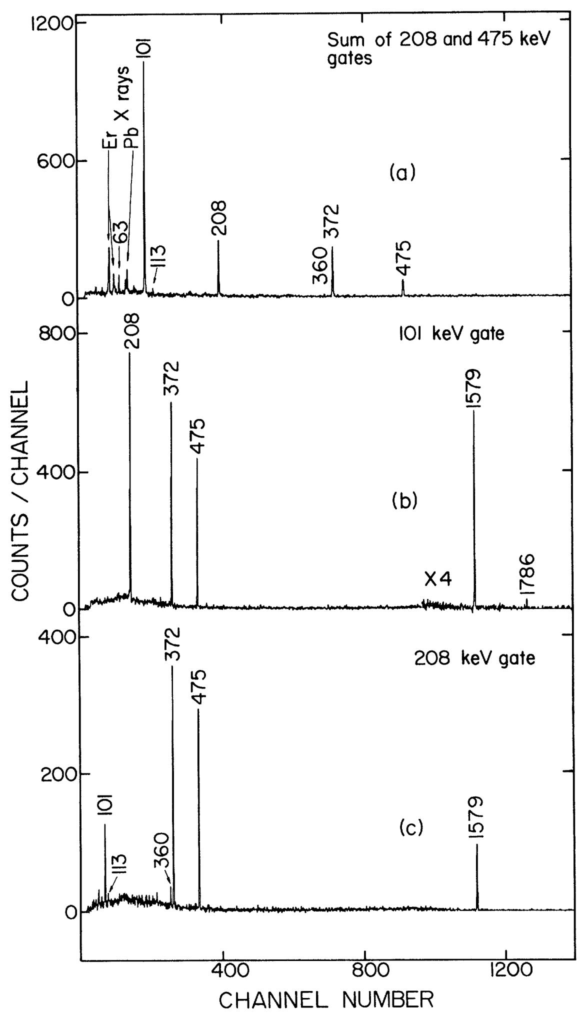

FIG. 2. Representative $\gamma\gamma$ coincidence spectra for ^{150}Er. Spectrum (a) was recorded with the planar detector, while spectra (b) and (c) were recorded with large Ge(Li) detectors.

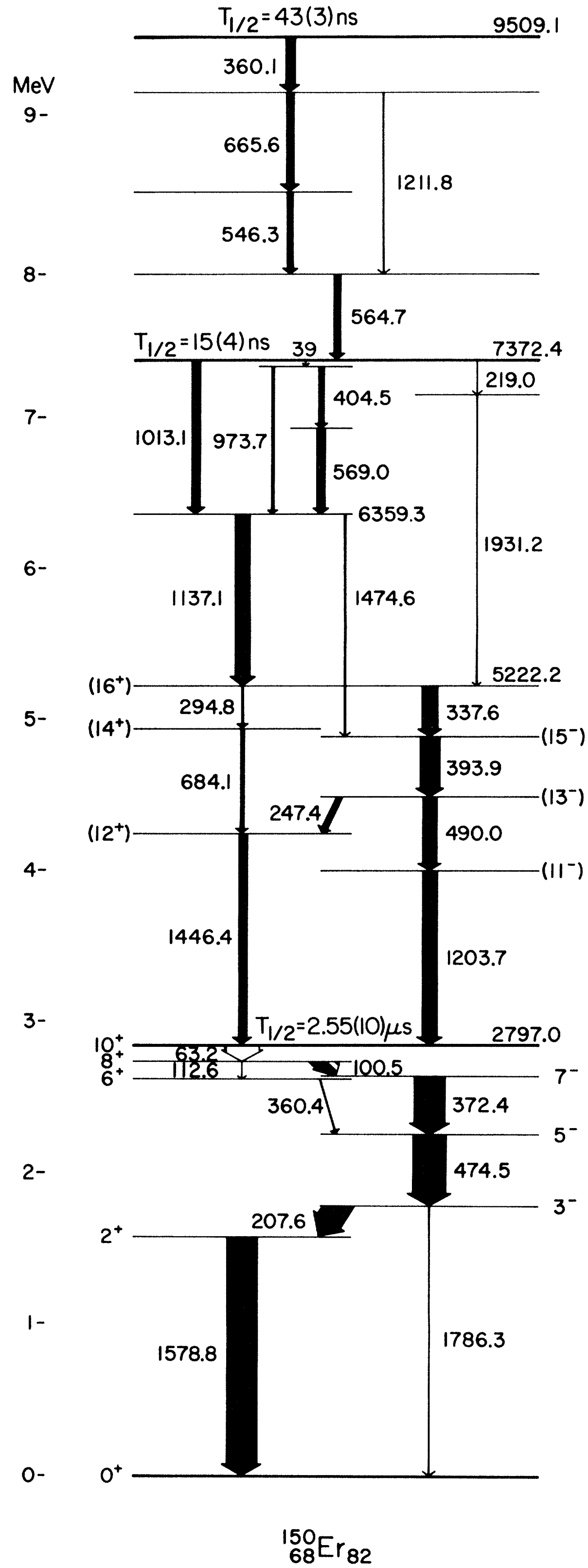

FIG. 3. The ^{150}Er level scheme. Widths of the transition arrows are proportional to the delayed transition intensities observed in the reaction 245 MeV ^{60}Ni+^{92}Mo. Where appropriate, internal conversion contributions are represented by unshaded portions of transition arrows.

tion; the half-life of the level populated by the 63-keV transition is approximately 20 ns. In addition, the weak 1786-keV crossover transition occurs parallel to the 208- and 1579-keV γ rays, and a 112.6-, 360.4-keV branch occurs parallel to the 100.5-, 372.4-keV portion of the main cascade. The relative γ-ray intensities observed in the ^{150}Tm decay established the ordering of the transitions unambiguously.

The resulting level scheme is shown in Fig. 3. For the 101- and 208-keV transitions, intensity balance requirements give the total conversion coefficients α_{tot}:

$$\alpha_{tot}(101\ \text{keV})=0.33\pm0.11$$

and

$$\alpha_{tot}(208\ \text{keV})<0.06\ ,$$

establishing $E1$ character for both transitions. Similarly, for the isomeric 63-keV transition the result is

$$\alpha_{tot}(63\ \text{keV})=17.3\pm3.5\ .$$

This value is consistent with $E2$ character only. The multipolarities of the 372, 475, and 1579 keV transitions could not be determined directly. However, the arguments for interpreting the 2797-keV 2.55-μs level as the expected $\pi h^4_{11/2}$ $v=2$ 10^+ isomeric state are compelling, and since the main cascade from this 10^+ state to the 0^+ ground state consists of one $E2$, two $E1$, and three other nonisomeric transitions, it is highly probable that the 372, 475, and 1579 keV are all $E2$ transitions. These considerations lead to the spin-parity assignments shown in Fig. 3. Overall, the decay pattern closely resembles that observed in the deexcitation of the ^{148}Dy $\pi h^2_{11/2}$ 10^+ isomer, except that the $E2$ transitions between the even-parity states in ^{150}Er compete less successfully with $E1$ branching to the odd-parity states.

C. The ^{150}Er level scheme above the 2.55 μs isomer

Delayed coincidence measurements across the 2.55-μs isomer identified strong 338-, 394-, 490-, 1204-keV, and many other transitions in ^{150}Er above the 2797-keV level. The cleanest spectra were obtained in a separate experiment, with a pulsed 1.5-μs on, 4.0-μs off, 245-MeV ^{60}Ni beam on a Pb-backed ^{92}Mo target, in which the γ rays feeding microsecond isomers were selectively enhanced. A Ge(Li) spectrometer, viewing the target directly, accepted (a) prompt γ-ray events, and (b) events occurring 13–93 ns after the time of reaction, only if they were followed during the subsequent beam-off period by the delayed triggering of the sum spectrometer. Spectra recorded in this fashion are shown in Fig. 4, and the energies and intensities of γ rays assigned to ^{150}Er are listed in Table II. The prompt/delayed intensity ratios were later useful in ordering the transitions in the level scheme.

All the transitions listed in Table II were also observed in coincidence measurements using the reaction ^{95}Mo+258 MeV ^{58}Ni$\rightarrow$^{153}Yb* and the recoil catcher technique. Representative coincidence spectra are presented in Fig. 5; these data were good enough to show definite coincidence relationships between stronger γ rays,

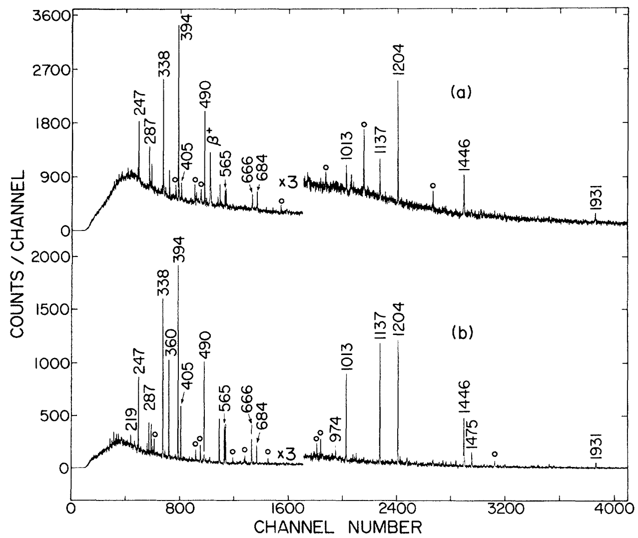

FIG. 4. Spectra recorded with a pulsed 245-MeV ^{60}Ni beam on a ^{92}Mo target, with a delayed triggering condition selectively enhancing the γ rays feeding the 2.55-μs isomer in ^{150}Er. Spectrum (a) shows the prompt γ rays, and spectrum (b) those occurring 13—93 ns after the compound nucleus reaction. All the observed γ rays are firmly identified as ^{150}Er transitions, except for those marked with circles.

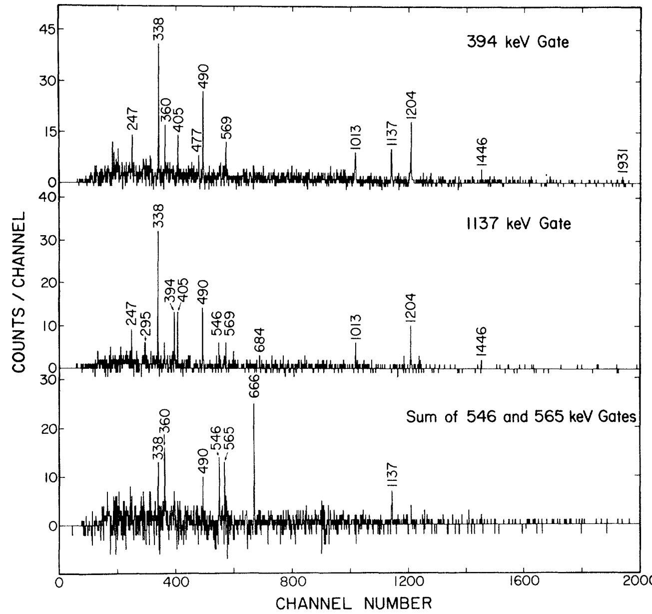

FIG. 5. Representative $\gamma\gamma$ coincidence spectra for transitions above the 2.55-μs isomer in ^{150}Er.

but the results for weaker lines were not always clear-cut. Analysis of the data established two parallel cascades of 338-, 394-, 490-, and 1204-keV γ rays and 295-, 684-, and 1446-keV γ rays between a level at 5222 keV and the 10^+ isomer (Fig. 3). The 247-keV transition connecting the two cascades was helpful in ordering the other transitions. Analysis of the $t_{\gamma\gamma}$ distributions (Fig. 6) revealed the existence of a 15±4 ns isomer at 7372 keV. The main decay of this isomer occurs by the 1013-keV transition to a 6359-keV level, which in turn deexcites by the 1137-keV γ ray to the 5222-keV level. Other cascades deexciting the 7372-keV isomer are also indicated in Fig. 3. They include the placement of a 39-keV isomeric transition, which was clearly seen in the appropriate coincidence gates, and of the 1931-keV γ ray feeding the 5222-keV level. A higher-lying isomer at 9509 keV deexcites by a main cascade of 360-, 666-, 546-, and 565-keV transitions to the 15-ns isomer; the half-life of this highest isomer was determined from the $t_{\gamma\,\mathrm{sum}}$ distribution (Fig. 6) to be 43±3 ns.

TABLE II. The energies, and prompt and delayed relative intensities of γ rays occurring in ^{150}Er above the 2.55 μs isomer. The prompt time range is 0—13 ns, and the delayed time range is 13—93 ns after compound nucleus formation.

E_γ (keV)	I_γ (prompt)	I_γ (delayed)
39.4±0.4		24±5
219.0±0.2	2.5±1.2	8±1
247.4±0.2	29±2	34±3
286.5±0.2	23±2	16±2
294.8±0.2	17±2	18±2
337.6±0.2	81±4	103±6
360.1±0.2	26±2	65±4
393.9±0.1	126±7	131±8
404.5±0.2	17±2	40±3
490.0±0.1	88±5	90±6
546.3±0.2	24±2	45±3
564.7±0.2	24±2	42±3
569.0±0.2	23±2	44±3
665.6±0.2	24±2	49±4
684.1±0.2	27±2	23±2
973.7±0.4	4±2	6±2
1013.1±0.3	23±3	60±4
1137.1±0.2	36±3	92±6
1203.7±0.1	100	100
1211.8±0.4	2±1	7±2
1446.4±0.2	52±4	50±4
1474.6±0.4	12±2	15±3
1931.2±0.4	16±2	9±2

The prompt and delayed intensities listed in Table II indicate substantial prompt feeding of the 5222-keV level (and the levels below it). Therefore, we performed angular

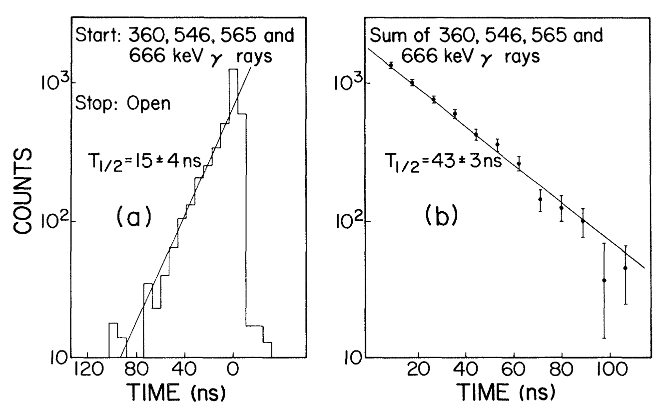

FIG. 6. (a) the $t_{\gamma\gamma}$ time distribution data used to determine the half-life of the 7372 keV isomer. (b) The $t_{\gamma\,\mathrm{sum}}$ time distribution used to determine the half-life of the 9509-keV isomer.

distribution measurements with the same setup as was used in acquiring the spectra of Fig. 4. However, for the γ rays of interest we obtained distributions so close to isotropic that reliable conclusions about their multipole order could not be drawn. The lifetimes of the levels involved are certainly less than a few nanoseconds, but apparently they are long enough for the paramagnetic relaxation in Er to destroy the spin alignment to a large extent.

Without knowing the transition multipolarities, a strong case can still be made for assigning spin-parity values to the ^{150}Er levels below 5.5 MeV, since the observed level structure up to this energy is relatively simple, and there is level-to-level correspondence with the results of shell-model calculations performed before the experiments. In the calculations, the $\pi h^4_{11/2}$ $I^\pi=16^+$ state is predicted to be clearly yrast, and the lowest level with $I>16$ is expected at least 1 MeV higher. The level at 5222 keV is interpreted as this 16^+ state, with the three γ-ray cascade to the 10^+ isomer proceeding through 14^+ and 12^+ levels of mainly $\pi h^4_{11/2}$ $v=4$ character; the observed transition energies agree quite well with the calculated[6] 16^+-14^+, 14^+-12^+, and 12^+-10^+ energy spacings. Three other levels between 2.8 and 5.2 MeV are expected to be populated in the deexcitation of the 16^+ level: an 11^- state (of $10^+\times 3^-$ octupole character), and 13^- and 15^- levels with the main $v=4$ configurations $\pi h^3_{11/2}s_{1/2}$ and $\pi h^3_{11/2}d_{3/2}$, respectively. As will be described in Sec. III, the 11^- state is calculated 1170 keV above the 10^+ isomer, while the predicted 13^--15^- and 15^--16^+ energy spacings are 390 and 367 keV. As can be seen (Fig. 3), the experimental energies match these predictions, with a maximum discrepancy of only 34 keV.

The $I^\pi=16^+$ $\pi h^4_{11/2}$ state is the highest spin configuration arising from valence protons only, and the generation of higher spins must involve excitation of the ^{146}Gd core. The yrast line is likely to continue above the 5222-keV level by coupling to collective or proton particle-hole core excitations, and then to neutron excitations. The probable structures of some of the higher levels observed are discussed briefly later. However, it is obvious that further measurements will be necessary to elucidate the ^{150}Er level structure above 5.5 MeV. Determinations of transition multipolarities by conversion electron measurements would be particularly valuable.

III. DISCUSSION

A. $\pi h^4_{11/2}$ states in ^{150}Er

The energy spacings between the states of configuration $\pi h^4_{11/2}$ in ^{150}Er have been calculated[6] using empirical two-body interaction matrix elements for $h_{11/2}$ protons taken from the complete $\pi h^2_{11/2}$ spectrum[3] in the two-valence-proton nucleus ^{148}Dy. The 10^+ and 8^+, and to a lesser extent the 6^+, states in ^{148}Dy should have rather pure $\pi h^2_{11/2}$ configurations, whereas the 4^+, 2^+, and especially the 0^+ ground state probably contain significant admixtures of other configurations. Since the calculation for the fully aligned 16^+ state in ^{150}Er depends on the ^{148}Dy 10^+, 8^+, and 6^+ energies only, the calculated energies of the ^{150}Er $h^4_{11/2}$ states have been normalized by matching the energy of the 16^+ state to the experimental value 5222 keV. Of the 33 $\pi h^4_{11/2}$ states calculated (Fig. 7), those expected to be yrast are the 12^+, 14^+, and 16^+ of seniority four; 2^+, 4^+, 6^+, 8^+, and 10^+ of seniority two; and the 0^+ ground state. Yrast levels corresponding to all of these except the 4^+ state have been located in the experiment (Fig. 7). Overall, the agreement between experimental and calculated energies is quite good.

A description of the actual yrast levels of ^{150}Er in terms of pure $\pi h^4_{11/2}$ configurations may be appropriate for $v=4$ states, but is likely to be less accurate for $v=2$ states, and poor for the $v=0$ ground state. The problem is that significant contributions of $\pi s^2_{1/2}$, $\pi d^2_{3/2}$, and other terms to 0^+ pairs are to be expected. The observed discrepancy between theory and experiment for the 2^+, 6^+, 8^+, and 10^+ energies is $\sim$250 keV in each case, indicating that the influence of the 0^+ pair is about the same for these levels of the same seniority. The calculated ground state energy is too low by 360 keV. These findings are generally consistent with those obtained for the three-valence-proton nucleus ^{149}Ho, where the spacing between the aligned $\pi h^3_{11/2}$ $\frac{27}{2}^-$ $v=3$ state and the $\frac{11}{2}^-$ $v=1$ ground state is calculated 119 keV larger than observed.[4] By considering the fractional parentage decomposition of the ^{150}Er $\pi h^4_{11/2}$ 16^+ state into simpler $\pi h^n_{11/2}$ substructures, corresponding to specific known levels in the lighter $N=82$ nuclei, the ^{150}Er ground state mass has already been determined[12] using the 16^+ excitation energy reported here. This result has provided an important extension of the $N=82$ two-proton separation energy systematics in the vicinity of $Z=64$.

A pragmatic way to improve the shell model calculation of $\pi h^4_{11/2}$ energies in ^{150}Er, which should work whatever the reasons for the deviations, is to incorporate experimental information[4] on $\pi h^3_{11/2}$ energies in ^{149}Ho. The calculation then involves a two-step fractional parentage reduction of $\pi h^4_{11/2}$ into $\pi h^3_{11/2}$ and $\pi h^2_{11/2}$, combining the

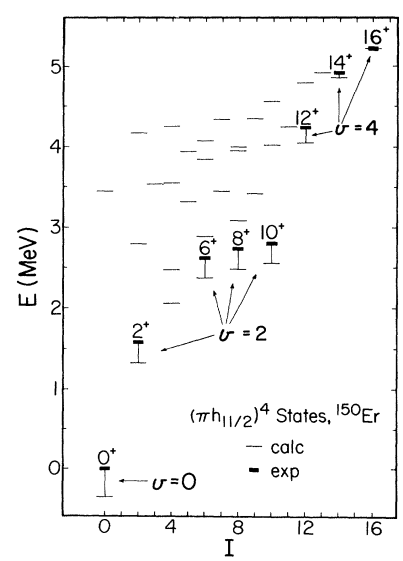

FIG. 7. Comparison of the calculated (Ref. 6) $\pi h^4_{11/2}$ energies in ^{150}Er with the experimental level energies. The calculated energies are normalized with respect to the energy of the 16^+ state, which is matched to the experimental value of 5222 keV.

empirical ^{149}Ho and ^{148}Dy energies with the corresponding coefficients of fractional parentage. This procedure amounts to including the effects of a weak phenomenological three-body interaction. Unfortunately, not all $\pi h^3_{11/2}$ energies in ^{149}Ho are known. However, for a calculation of the yrast 16^+, 14^+, 12^+, and 10^+ states this is not a major shortcoming, since more than 80% of their three-particle contents lie in the known $\frac{27}{2}^-$, $\frac{23}{2}^-$, $\frac{19}{2}^-$, $\frac{15}{2}^-$, and $\frac{11}{2}^-$ states. Using this method, the calculated transition energies $16^+ \to 14^+ \to 12^+ \to 10^+$ become 308, 700, and 1441 keV, which compare much better with the experimental values 295, 684, and 1446 keV, than the energies 361, 814, and 1491 keV obtained when only the ^{148}Dy two-body energies are used.[6]

B. Octupole excitations

The 3^- octupole state at 1579 keV in the ^{146}Gd core nucleus has a dominant $\pi h_{11/2} d^{-1}_{5/2}$ component, involving promotion of a proton across the $Z=64$ gap. In ^{148}Dy, the corresponding 3^- state is found at 1688 keV. The upward energy shift of 1688-1579=109 keV has been interpreted[3] as a Pauli interference effect arising from coupling of the 3^- excitation to the $\pi h^2_{11/2}$ component of the ^{148}Dy 0^+ ground state. The ^{150}Er nucleus, with four valence protons, has a second 0^+ pair contributing to its ground state, and its 3^- energy is therefore predicted to be 1579+2(109)=1797 keV, which is in good agreement with the observed 1786 keV. The $B(E1;3^- \to 2^+)/B(E3;3^- \to 0^+)$ branching ratios in ^{148}Dy and ^{150}Er are equal within a factor of 2.

In ^{148}Dy, the yrast line continues above the $\pi h^2_{11/2}$ 10^+ state by coupling to the octupole excitation,[3] and the lowest member of the $10^+ \times 3^-$ multiplet is an 11^- level located 1061 keV above the 10^+ state. An analogous 11^- level of $10^+ \times 3^-$ type should occur in ^{150}Er, but since an additional 0^+ pair contributes to the ^{150}Er 10^+ $v=2$ state, one would expect a similar Pauli shift here, giving a predicted 11^--10^+ spacing of 1061+109=1170 keV. The corresponding experimental level is found 1204 keV above the ^{150}Er 10^+ isomer.

C. Seniority two and four $\pi h^3_{11/2} s_{1/2}$ and $\pi h^3_{11/2} d_{3/2}$ states

In addition to the 3^- octupole state, 5^- and 7^- levels at 2350 and 2739 keV occur below the 10^+ isomer in ^{148}Dy and are interpreted[3] as the lowest members of $\pi h_{11/2} s_{1/2}$ and $\pi h_{11/2} d_{3/2}$ multiplets. The ^{150}Er levels at 2261 and 2633 keV are similarly interpreted as 5^- and 7^- excitations with dominant $\pi h^3_{11/2} s_{1/2}$ and $\pi h^3_{11/2} d_{3/2}$ $v=2$ configurations, respectively. It is not possible to calculate the energies of these states because the $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$ single-quasiparticle energies in ^{149}Ho are unknown, but one would conclude from the similar 10^+-7^--5^- level spacings observed in ^{148}Dy and ^{150}Er that the proton single particle spacings in ^{147}Tb and ^{149}Ho are not very different.

Seniority four states of the type $\pi h^3_{11/2} s_{1/2}$ 13^- and $\pi h^3_{11/2} d_{3/2}$ 15^- are expected below the $\pi h^4_{11/2}$ 16^+ state. The angular momenta of $s_{1/2}$ or $d_{3/2}$ are coupled to $h^3_{11/2}$ so that the maximum singlet-spin attraction is achieved in both cases. One can calculate the 16^+-15^--13^- spacings despite the lack of knowledge of one-quasiparticle energies. This has been done using the known $(\pi h^3_{11/2})\ \frac{27}{2}^-$, $(\pi h^2_{11/2} d_{3/2})\ \frac{23}{2}^+$, and $(\pi h^2_{11/2} s_{1/2})\ \frac{19}{2}^+$ energies in ^{149}Ho, and the 10^+, 7^-, and 5^- energies in ^{148}Dy, together with small ($\sim$50 keV) two-body correction terms. The calculated 16^+-15^- and 15^--13^- spacings are 367 and 390 keV, respectively. It is largely on the basis of this result that the 338- and 394-keV sequence deexciting the 16^+ level is confidently interpreted as the correspondingly $16^+ \to 15^- \to 13^-$ cascade.

D. $E2$ transition rates and subshell occupation number

The measured half-life of the ^{150}Er 2797-keV level gives for the isomeric transition between the 10^+ and 8^+ states of seniority two:

$$B(E2;63\ \text{keV},{}^{150}\text{Er})=11.3\pm0.4e^2\,\text{fm}^4\ .$$

This result can be compared with the value determined[3] for the corresponding $10^+ \to 8^+$ transition in ^{148}Dy:

$$B(E2;86\ \text{keV},{}^{148}\text{Dy})=43\pm3e^2\,\text{fm}^4\ .$$

This type of isomerism involving j^n states of the same seniority occcurs in many nuclei near closed shells. Lawson[6] has pointed out that when seniority is conserved the $E2$ transition rates between $\pi h^n_{11/2}$ states of the same seniority should be proportional to $(6-n)^2$, where n is the $\pi h_{11/2}$ subshell occupation number. Assuming $n=2$ in ^{148}Dy and $n=4$ in ^{150}Er thus leads to a prediction that the $10^+ \to 8^+$ transition in ^{150}Er should be four times slower than the corresponding transition in ^{148}Dy. The measured $B(E2)$ values are in excellent accord with this prediction.

A broader survey[13] of $E2$ transition rates between $\pi h^n_{11/2}$ $v=2$ and $v=3$ states in ^{148}Dy, ^{149}Ho, ^{150}Er, ^{151}Tm, and ^{152}Yb has shown that the $B(E2)$ values in these five $N=82$ nuclei are fitted very well with the *same* $\pi h_{11/2}$ effective charge, and that the agreement between theory and experiment is here better than has been observed in j^n excitations around traditional doubly magic nuclei.

E. The ^{150}Er levels above 5222 keV

As we have mentioned, $I^\pi=16^+$ is the highest spin configuration arising from valence protons alone, and higher spin states must involve excitation of the ^{146}Gd core. The maximum spin proton four-quasiparticle (4qp) state is 17. The 17^- state of the configuration $\pi h^3_{11/2} g^{-1}_{7/2}$ is known[14,15] in ^{146}Gd (7165 keV) and ^{148}Dy (6263 keV), in both cases about 3.3 MeV above the $\pi h^2_{11/2}$ 10^+ state. Hence, the corresponding 17^- state in ^{150}Er should come at about 6.1 MeV. The association of the experimental level at 6359 keV with this state seems very probable. The 1475 keV decay branch to the $\pi h^3_{11/2} d_{3/2}$ 15^- level is then naturally understood as a $g_{7/2} \to d_{3/2}$ $E2$ transition, somewhat hindered by a pairing factor $(U_1U_2-V_1V_2)^2$, since $g_{7/2}$ is mainly a hole and $d_{3/2}$ mainly a particle, but still competitive with a $17^- \to 16^+$ $E1$ transition.

States with spins higher than 17 can be formed by adding a particle-hole excitation to the 4qp states, resulting in

6qp states. The lowest particle-hole excitation in ^{146}Gd is 3^- at 1.58 MeV, and one may assume that yrast states in ^{150}Er of the nature 4qp$\times 3^-$ occur not far above the 6359-keV level. The observed levels at 6928 and 7333 keV may be of this type. The 7153-keV level, deexciting by the 1931-keV transition to the 16^+ state, probably has the structure 4qp$\times 2^+$, and is a counterpart of the first 2^+ state at 1971 keV in the ^{146}Gd core, and of the (2qp$\times 2^+$) 12^+ state located by Julin *et al.*[15] 1933 keV above the $\pi h^2_{11/2}$ 10^+ isomer in ^{148}Dy. On the other hand, the 15-ns isomer at 7372 keV is not easily understood as a pure proton state. Instead, it may involve the excitation of one or two neutrons across the $N=82$ gap, analogous to the 550-ns isomer[16,17] in ^{147}Gd. The states above 7.5 MeV then manifest the interplay between the degrees of freedom of protons and neutrons, resulting in a more complex situation from the point of view of the shell model description.

IV. CONCLUSIONS

Continuing a series of studies of proton-rich $N=82$ nuclei with n valence protons outside the ^{146}Gd core, we have established the yrast level of the four-valence-proton nucleus ^{150}Er up to a $T_{1/2}=43$-ns isomeric state at 9509 keV. The levels up to 2.8 MeV, and those between 2.8 and 5.3 MeV, are interpreted as seniority two and four shell model states involving the valence protons only. The observed energy spacings between levels with dominant $\pi h^4_{11/2}$ configurations agree reasonably with those calculated using empirical two-body interactions from ^{148}Dy; they agree significantly better with predictions of a more detailed shell model treatment taking account of phenomenological three-body effects by considering also the known $\pi h^3_{11/2}$ energies in ^{149}Ho. The measured $B(E2;10^+\rightarrow 8^+)$ in ^{150}Er is almost exactly the predicted factor of 4 smaller than that observed for the corresponding transition in ^{148}Dy, illustrating the influence of subshell occupation number on $E2$ transition probabilities. It would be most interesting to understand the extensive ^{150}Er level spectrum above 5.3 MeV observed in the present work, particularly the structures of two high-lying isomers. Further experimental studies are planned.

ACKNOWLEDGMENTS

We thank I. Ahmad and S. R. Faber for their participation in the early stages of this study, and R. D. Lawson for useful discussions. This work was supported by the U. S. Department of Energy.

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