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Single-particle states in ^{149}Er and ^{149}Ho, and the effect of the $Z=64$ closure

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The decay of ^{149}Er was investigated by γ-ray spectroscopy. Based on these measurements the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ neutron states in ^{149}Er and the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ proton states in ^{149}Ho were identified. A systematic examination of these proton states in $N=82$ isotones indicates a modest closure at $Z=64$, rather than a major one as suggested previously. Spherical Hartree-Fock-Bogoliubov calculations for even-Z $N=81$ and odd-Z $N=82$ nuclei are compared with experiment.

The investigation of low-lying levels in nuclei with a few particles (or holes) above closed-shell configurations is of considerable interest because these levels are relatively pure shell-model states and they provide us with an excellent opportunity for comparison with calculations based on various models. These models have sets of phenomenological parameters which can be improved by being fit to experimental results. The goal is to arrive at a universal description of single-particle properties.

We have been involved in studying decay properties of isotopes near the 82-neutron shell and the 64-proton subshell to obtain structure information for even-Z nuclei with $N=81$ and $N=83$, and, for odd-Z nuclei with $N=82$. Of relevance to the present investigation was our study of ^{147}Dy^{m} and ^{147}Dy^{g} decays wherein we identified the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ neutron states in ^{147}Dy,[1] and the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ proton states in ^{147}Tb.[2] (A concurrent study[3] arrived at the same low-lying structure in ^{147}Tb.) Our immediate interest was to extend these single-particle level systematics to ^{149}Er and ^{149}Ho and a search was begun for the unknown nuclide ^{149}Er. In a series of ^{12}C+^{144}Sm bombardments we identified[4] ^{149}Er *via* its β-delayed-proton activity to be a (9 ± 1)-s isotope. With this half-life information in hand we now have investigated its β-decay properties.

As in the earlier study[4] ^{149}Er was first produced in the ^{144}Sm (^{12}C, $7n$) reaction. A 2.1-mg/cm^2-thick samarium metal foil, enriched in ^{144}Sm to 96.5%, was irradiated with 135-MeV ^{12}C ions from the Oak Ridge Holifield Heavy Ion Research Facility tandem accelerator. Products recoiling out of the target were thermalized in helium gas and transported to a shielded area for singles and coincidence measurements with γ- and x-ray detectors. To obtain more definitive information, particularly for the ^{149}Er isomeric decay, we also produced the isotope in the ^{94}Mo(^{58}Ni, $n2p$) reaction at the Lawrence Berkeley Laboratory SuperHILAC and mass separated it with the OASIS on-line separator.[5] The ^{58}Ni beam energy at the center of the target was 262 MeV while the ^{94}Mo metal foil, enriched to 93.9%, was 2.0 mg/cm^2 thick. Singles and coincidence γ- and x-ray data were once again accumulated, as well as data on delayed-proton decay.

Table I summarizes energies and relative intensities for transitions that were assigned unequivocally to ^{149}Er decay on the basis of measured half-lives, γ-ray coincidence relationships, and energies of coincident K x rays. A cascade of three γ rays (171.2, 343.9, and 436.9 keV) follows ^{149}Er β decay while two transitions (111.0 and 630.5 keV) in coincidence with one another are ascribed to ^{149}Er isomeric deexcitation.

According to the shell model ^{149}Er, in its ground state, has four protons in the $h_{11/2}$ shell above $Z=64$ and one neutron in the $s_{1/2}$ shell just below $N=82$; the $h_{11/2}$ and $d_{3/2}$ neutron orbitals are full. A large part of the $(\beta^{+}+\epsilon)$ decay strength is expected to go to high energy levels in ^{149}Ho with $[(3\pi h_{11/2}, \nu h_{9/2})+\nu s_{1/2}]$ configurations following the $\pi h_{11/2}\rightarrow \nu h_{9/2}$ transition. Other high-lying levels could receive less direct feeding, following the $\pi d_{5/2}\rightarrow \nu f_{5/2}$, $\nu f_{7/2}$,

TABLE I. Transition energies and intensities.

Nucleus	E_γ (keV)	Relative intensities I_γ	$I_\gamma+I_{\mathrm{ce}}$
^{149}Er	111.0 ± 0.1	100[a]	316
^{149}Er	630.5 ± 0.3	248 ± 25	329 ± 33
^{149}Ho	171.2 ± 0.1	100[a]	158[b]
^{149}Ho	343.9 ± 0.2	58 ± 5	63 ± 6[b]
^{149}Ho	436.9 ± 0.2	33 ± 5	35 ± 6[b]

[a] Normalization points for ^{149}Er and ^{149}Ho transitions.
[b] Assumed $M1$ multipolarity for I_{ce} determination.

$\nu p_{3/2}$, $\pi g_{7/2} \rightarrow \nu f_{5/2}$, $\nu f_{7/2}$, $\nu h_{9/2}$, or $\pi h_{11/2} \rightarrow \nu i_{13/2}$ first forbidden transitions.

The ^{149}Er isomeric state, based on systematics of orbitals in $N=81$ isotones, has one hole in the $h_{11/2}$ neutron orbital while the $d_{3/2}$ and $s_{1/2}$ orbitals are full. In addition to the β transitions mentioned above (which now populate high energy states with similar configurations but where the $\nu h_{11/2}^{-1}$ orbital has replaced the $\nu s_{1/2}$ state) the $\pi h_{11/2} \rightarrow \nu h_{11/2}$ transition, leading to the low-lying $h_{11/2}$ state of ^{149}Ho is also expected.

In accord with the above discussion we did indeed observe numerous γ rays ranging from 1 to 2.5 MeV and decaying with about a 10-s half-life. Therefore, some of the ^{149}Er β decay, as in the case of ^{147}Dy,[6] proceeds to high-lying levels in ^{149}Ho. However, since we were concerned primarily with locations of the low-lying single-particle states, deexcitation of high energy levels was not unraveled in this work. The proposed partial decay scheme is shown in Fig. 1.

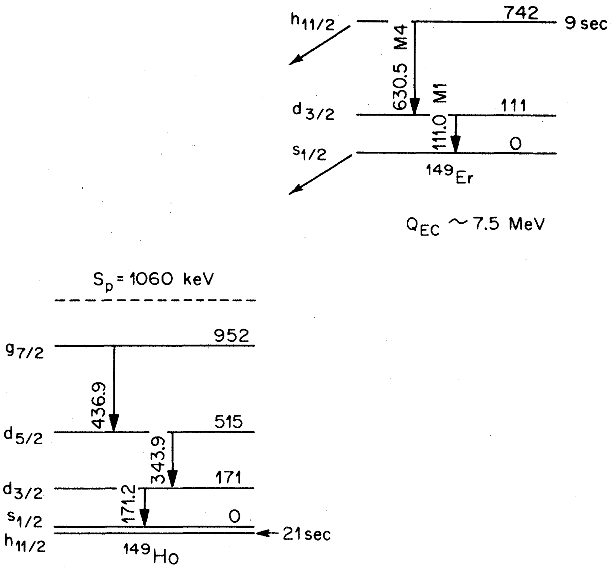

FIG. 1. Partial decay scheme for ^{149}Er. The isomeric branch is estimated to be 2.7%; see text for discussion.

The lowest available five levels in odd-Z $N=82$ isotones[2,3] are the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ proton orbitals. Because the three cascading γ rays assigned to ^{149}Er β decay are in prompt coincidence they must connect the four positive parity states. Their placement (see Fig. 1) is based on their intensities which are summarized in Table I. Since crossover transitions were not observed and the deexcited levels have short half-lives the spin sequence must be monotonic: $g_{7/2} \rightarrow d_{5/2} \rightarrow d_{3/2} \rightarrow s_{1/2}$, the same as in ^{147}Tb.

The order of the proton states in ^{147}Tb and ^{149}Ho is very different from those in $N=82$ nuclei with $Z \leqslant 63$ where the $g_{7/2}$ and $d_{5/2}$ orbitals are below the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ states. This is due to the fact that the $g_{7/2}$ orbital is a hole state for $Z \geqslant 59$ and that the $d_{5/2}$ orbital becomes a hole state in ^{147}Tb. With this in mind proton level systematics for $N=82$ isotones are plotted in Fig. 2(a) with hole states indicated as having negative energies. (We show the $h_{11/2}$ and $s_{1/2}$ orbitals in ^{149}Ho almost degenerate though the en-

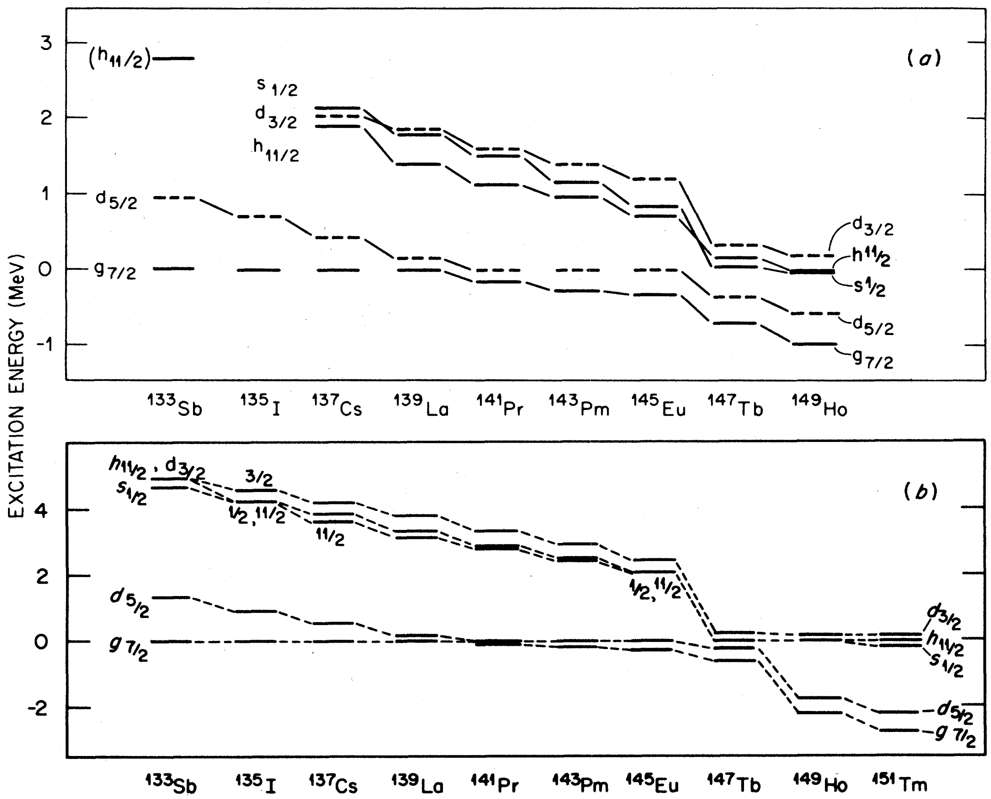

FIG. 2. Energy systematics of single-proton states in odd-Z $N=82$ isotones: (a) experimental; (b) HFB calculations (see text).

ergy difference is not known experimentally.) One sees that the levels in ^{147}Tb and ^{149}Ho in fact do fit the overall trend and the effect of the $Z=64$ closure is clearly not as pronounced as had been concluded in Ref. 3. Rather our data support a more modest gap at $Z=64$ as also implied by α-decay energy systematics (see, e.g., Ref. 7) and α-decay transition rates.[8]

Single-particle energies for nuclei in this mass region have been calculated previously (see, e.g., Refs. 3, 9, and 10) by using phenomenological interactions with adjustable parameters. We performed spherical Hartree-Fock-Bogoliubov (HFB) calculations with realistic interactions in a core-plus-particle description for $N=82$ odd-Z nuclei from ^{133}Sb to ^{151}Tm. Equations are given in Ref. 11, while the model space and core energies are in Ref. 12. The interaction is the Brueckner G matrix derived from the Reid soft-core potential.[13] Pairing gaps and single nucleon energies are calculated with this interaction. Core energies were chosen so that the HFB single-particle energies coincide with the deduced[14] single-particle energies in ^{146}Gd. Because the Hartree-Fock gap is so large, no pairing is obtained in ^{146}Gd. The calculated spectra are shown in Fig. 2(b). The theoretical trends agree with experiment. However, the scale of the excitation energies is too large, probably because the effective interaction is too strong. If the single-particle gap at $Z=64$ is cut in half, then large pairing is obtained in ^{146}Gd and the two-quasiparticle gap is reduced by 11%.

The ^{149}Ho level spectrum has the main features predicted by Wenes *et al.*[9] who used a fixed BCS approximation to calculate the energies of the single proton quasiparticle states in ^{149}Ho and ^{151}Tm. Their splitting between the $d_{5/2}$ and $d_{3/2}$ orbitals, however, is about twice as large as our experimental value.

For the isomeric decay, as indicated in Fig. 1, we propose that the 630.5- and 111.0-keV transitions connect the following ^{149}Er neutron states: $h_{11/2} \rightarrow d_{3/2} \rightarrow s_{1/2}$. From the spectrum gated by the 630.5-keV γ ray it was possible to deduce the 111.0-keV transition multipolarity by comparing its intensity with the intensities of the erbium K x rays. The K-shell conversion coefficient of this γ ray was thus determined to be 1.8 ± 0.2, in agreement with the theoretical value of 1.81 for an $M1$ transition. By the same method we also determined the K-shell conversion coefficient of the 630.5-keV transition to be 0.3 ± 0.1, in agreement with the theoretical value of 0.247 for an $M4$ transition.

Figure 3 shows the energy systematics of the $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ neutron states in even-Z, $N=81$ nuclei ranging from ^{131}Sn to ^{149}Er. With the exception of ^{149}Er (present study) and ^{131}Sn (Ref. 15) the experimental information in Fig. 3(a) represents results summarized in Ref. 1 and updated by scanning appropriate Nuclear Data Sheets. One sees that the ^{149}Er levels fit well into the systematics. Included are the $M4$ transition energies, and, where isomeric branchings are known, transition rates expressed in

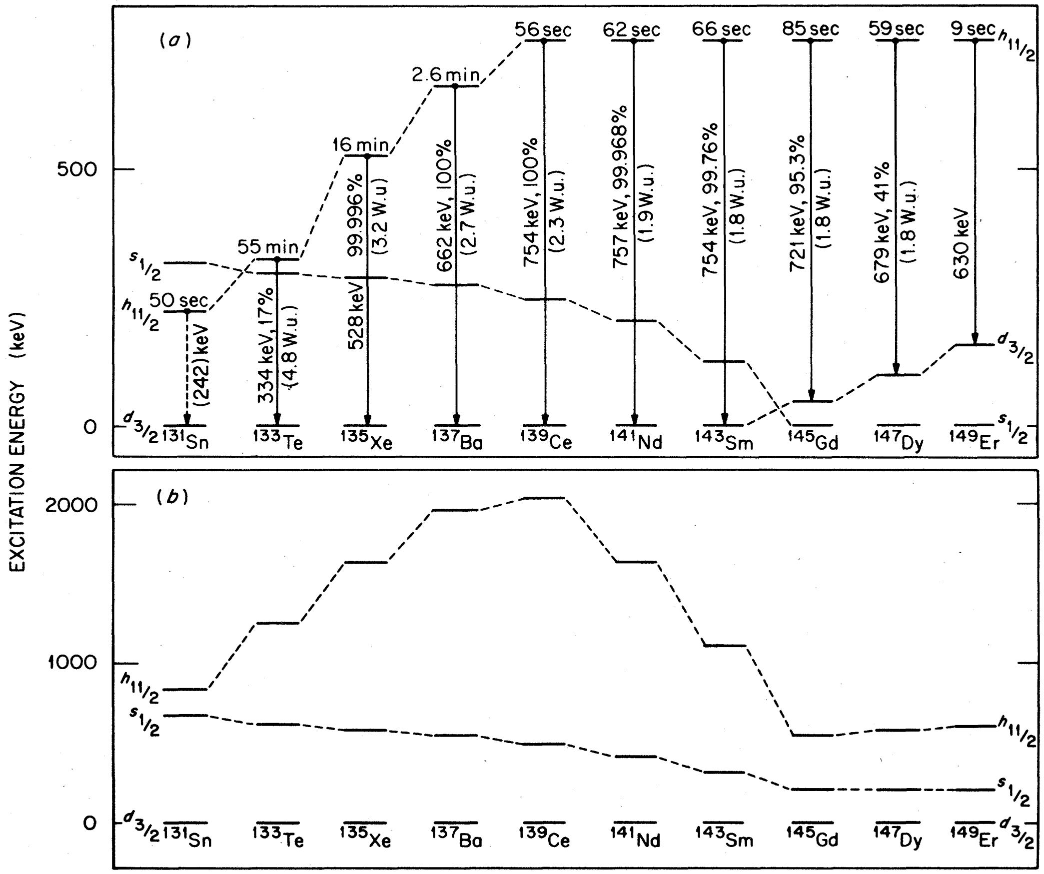

FIG. 3. Location of $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ neutron states in even-Z $N=81$ iostones: (a) experimental; (b) HFB calculations (see text). Intensities and Weisskopf factors are included in part (a) for the $M4$ transitions that connect the $h_{11/2}$ and $d_{3/2}$ levels.

Weisskopf units. These experimental enhancements are essentially constant for $Z \geqslant 58$. By using the leveled-off Weisskopf unit of 1.8 for the 630.5-keV transition we estimate the isomeric branch for $^{149}\mathrm{Er}^m$ to be 2.7%.

We also performed the HFB calculations for these $N = 81$ isotones. The calculations [see Fig. 3(b)] reproduce the experimental behavior of the splitting between the $h_{11/2}$ and $d_{3/2}$ neutron orbitals. This splitting increases with increasing Z, reaches a maximum at $Z = 56$–58, and then begins to decrease as a result of proton pairs filling first the $g_{7/2}$ and then the $d_{5/2}$ orbitals. (A similar conclusion was reached by Silverberg[10] who considered isotones from ^{133}Te to ^{145}Gd.) However, the calculations do not explain why the experimental $h_{11/2}$ levels have a constant excitation energy for $Z \geqslant 58$.

It would be interesting to investigate the ^{151}Yb and ^{151}Tm levels, particularly since our calculations and those of Wenes *et al.*[9] predict that the $s_{1/2}$ and $d_{3/2}$ levels in ^{151}Tm are almost degenerate. We recently identified the β-delayed-proton branch of ^{151}Yb. The isotope has a half-life of about a second which means that the isomeric decay branch, using a Weisskopf unit of 1.8 and an estimated E_γ of 600 keV for the $h_{11/2} \rightarrow d_{3/2}$ transition, is $\sim 4\times10^{-4}$. Observation of the $M4 \rightarrow M1$ cascade in ^{151}Yb therefore might be very difficult. Study of the low-lying levels in ^{151}Tm, however, appears to be feasible. Such an investigation, together with the present study, should provide an opportunity for improving shell-model calculations in this mass region.

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