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Decay of the neutron-rich isotope ^{171}Ho and the identification of ^{169}Dy

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Neutron-rich rare-earth isotopes were produced in multinucleon transfer reactions between ^{170}Er ions and ^{nat}W targets. On-line mass separation was used together with β- and γ-ray spectroscopy in these studies. At mass $A=169$, the heaviest known dysprosium isotope, 39(8) s, ^{169}Dy, was identified. It was observed to β^- decay to the ground state of ^{169}Ho or through a level at 1578 keV. In the $A=171$ mass chain, a partial decay scheme for 55(3)-s ^{171}Ho was determined.

Recent successful searches at the On-Line Apparatus for SuperHILAC Isotope separation (OASIS) facility[1] for new neutron-rich rare-earth isotopes, with ^{176}Yb beams on ^{nat}W to produce ^{174}Er and ^{171}Ho,[2] have spurred further experiments using multinucleon transfer reactions with neutron-rich rare-earth beams. The SuperHILAC at the Lawrence Berkeley Laboratory provided high-intensity beams (50–125 pnA) of 8.5-MeV/nucleon ^{170}Er ions which impinged on a ^{nat}W target inside the OASIS ion source. The ^{nat}W targets were of sufficient thickness (>15 mg/cm^2) to degrade the ^{170}Er ions below the Coulomb barrier. Reaction products were ionized, mass analyzed, and the desired mass chain transported ionoptically to a shielded counting area. There, the activities were collected on a fast-cycling tape system and transported to a detector array for β- and γ-ray spectroscopy. A β telescope and low-energy (10–400 keV) γ-ray detector, consisting of a 718-μm Si detector and a planar hyperpure Ge (HPGe) detector, faced the radioactive layer of the tape. On the opposite side of the tape, a large solid angle ($\sim$35%) 1-mm-thick plastic scintillator, for electron detection, and 52% Ge detector, for γ-ray detection, were located. A 24% Ge detector was positioned at 90° with respect to the other detectors at a distance of $\sim$4.5 cm from the source. Time-resolved multispectrum singles data were acquired with the HPGe and 52% Ge detectors, where the tape cycles were divided into eight equal time intervals for half-life determinations. Coincidence events registered in the various detectors were recorded in an event-by-event mode.

At mass $A=169$, a search for the new isotope ^{169}Dy was undertaken. The expected Q_β value for this isotope was $\sim$3.2 MeV taking the average of the mass predictions compiled by Haustein.[3] Half-life predictions were 38 s, by Klapdor, Metzinger, and Oda[4] and 64 s, using the gross theory of β decay[5] and the Q_β value above. A tape cycle time of 160 s was therefore chosen to maximize this activity. High-energy β particles [Fig. 1(a)] were measured in the β telescope with energies extending beyond the β end points ($\sim$2.0 MeV for ^{169}Ho) of known $A=169$ isobars that could be expected to emerge from the ion source of the mass separator. The two-component decay fit of the background-subtracted β intensity between 2.1 and 3.2 MeV is shown in the inset of Fig. 1(a). The 43(11) s half-life obtained for the short-lived activity does not match any of the previously known β-decaying $A=169$ isobars. A Fermi-Kurie plot of the high-energy β^- particle singles data in the β telescope and a least-squares linear fit of the plot from 2.1 to 2.9 MeV yielded a β end point of 3.2(3) MeV [Fig. 1(b)]. Similar analyses of β^- particles decaying to the 853- and 941-keV levels in ^{169}Ho decay gave β end points of 1.3(1) and 1.2(1) MeV, respectively, in good agreement with 1.3 and 1.2 MeV found in the literature.[6] Close inspection of the γ-ray singles spectra yielded only one short-lived γ ray at 1578.2(4) keV with a half-life of 35(11) s. No Ho K x rays were observed and all other γ rays were longer lived. The event-by-event data showed the 1578-keV γ ray to be in coincidence with the β^- particle spectrum shown in Fig. 2. Statistics were too poor to obtain a β end point us-

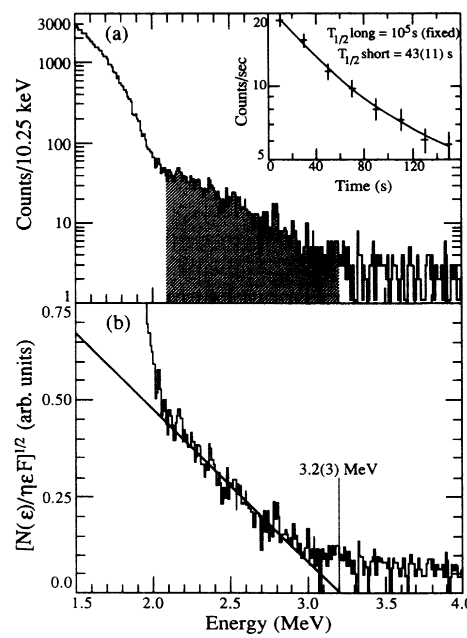

FIG. 1. β-decay data for the $A=169$ mass chain; (a) β particle spectrum measured in the β telescope and (b) Fermi-Kurie plot and least-squares linear fit from 2.1 to 2.9 MeV resulting in a β end point of 3.2(3) MeV. The inset in (a) shows the two-component background-subtracted decay of the β intensity between 2.1 and 3.2 MeV (shaded portion of the spectrum).

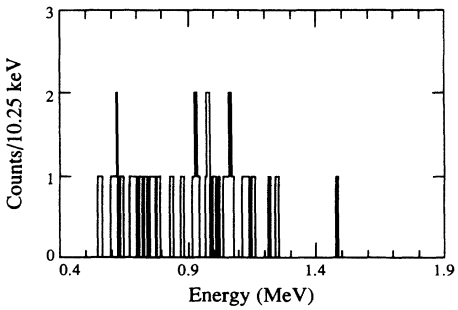

FIG. 2. β particle spectrum measured in coincidence with 1578-keV γ rays in the $A = 169$ mass chain.

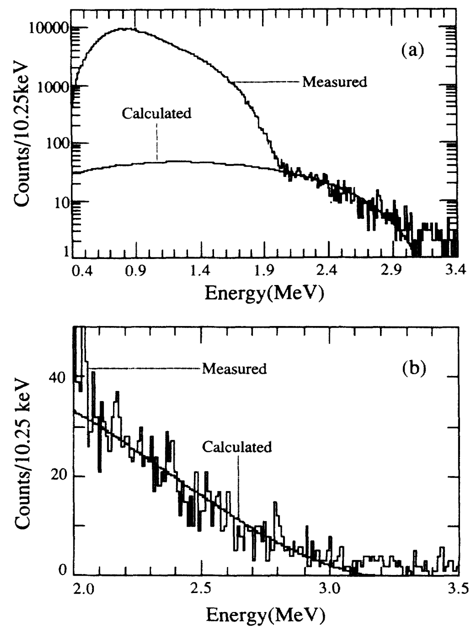

FIG. 4. Fit of the measured $A = 169$ β^- spectrum with the calculated β^- spectrum using a 3.2-MeV end point, normalized to the 2.1–2.9-MeV interval; (a) entire spectrum and (b) the 2.0–3.5-MeV region of the spectrum.

ing Fermi-Kurie analysis, but visual inspection of the spectrum indicates an end point of ~1.5 MeV, which is consistent with the measured decay energy of 3.2(3) MeV. A maximum-likelihood-decay fit of the time data for the β^- particles in Fig. 2 yielded a half-life of $58(^{+32}_{-16})$ s. Based on the agreement between both the experimental decay energy and half-life with the predictions, we assign the observed activity to the new isotope ^{169}Dy with a half-life of 39(8) s as determined from the weighted average of both the γ and β half-lives.

Our proposed partial decay scheme for ^{169}Dy is shown in Fig. 3. The intensity of the ground-state β branch was estimated by fitting the 2.1–2.9-MeV interval of a calculated "ideal" β particle spectrum, with a 3.2-MeV β end point, to the measured β spectrum to determine the total integral of β particles in the spectrum. The fit of the calculated to the measured β spectrum is shown in Fig. 4. The β telescope efficiency was calculated in a separate experiment using the above procedure on β particles with ~2.0-MeV end points from ^{168}Ho decay,[7] gated on γ rays detected in the 52% Ge detector. A ground-state to excited-state (1578 keV) β branching ratio of 3.5 was determined with an estimated uncertainty of ~20% due to possible errors in the calculated spectrum fit and to take into account that the β telescope efficiency may change with β particle energy. The decay scheme is consistent with the lack of Ho K x rays since there should be little internal conversion.

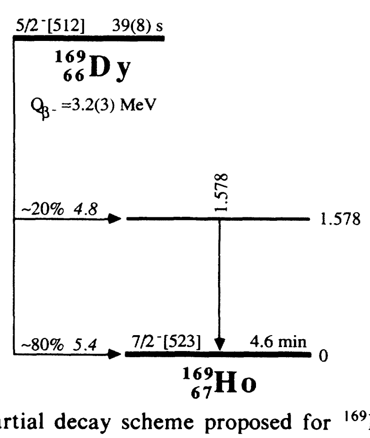

FIG. 3. Partial decay scheme proposed for ^{169}Dy. Energies are in MeV. The Q_β value was determined in this experiment. The log*ft*'s are in italics.

For ^{169}Dy and ^{169}Ho, the assignments of the 103rd neutron and 67th proton orbitals, $\frac{5}{2}^-$[512] and $\frac{7}{2}^-$[523], respectively, are experimentally well established for this region. All odd holmium isotopes from ^{157}Ho to ^{169}Ho have $\frac{7}{2}^-$[523] ground-state configurations[7] and the $N = 103$ isotones ^{175}Hf, ^{173}Yb, and ^{171}Er have $\frac{5}{2}^-$[512] ground-state assignments.[7] Our measured log*ft* = 5.4 for the ground-state branch is consistent with a log*ft* = 5.8 for the $\frac{7}{2}^-$[523] proton to $\frac{5}{2}^-$[512] neutron transition reported in the decay of ^{167}Ho, but it is lower than the log*ft* = 6.4 for the $\frac{5}{2}^-$[512] neutron to $\frac{7}{2}^-$[523] proton transition previously measured in ^{171}Er decay.[7] The log*ft* = 4.8 for the β feeding to the level at 1578 keV is faster than any known β transition involving the $\frac{5}{2}^-$[512] neutron level. The 1578-keV level could possibly be a three quasiparticle state composed of $\frac{7}{2}^-$[523] proton and $\frac{5}{2}^-$[512] neutron particle states and a $\frac{5}{2}^-$ [523] neutron hole state. This assignment would have a resulting $\frac{7}{2}^-$ spin and parity which is consistent with both Gamow-Teller allowed β feeding and a strong ground-state γ transition. However, the excitation energy may be somewhat low for such a configuration and the 1578-keV level has, therefore, been left unassigned. The tentative assignments of the $\frac{5}{2}^-$[512] neutron level to the 39-s ^{169}Dy parent and the $\frac{7}{2}^-$[523] proton orbital to the measured ^{169}Ho ground state are in agreement with nuclear level predictions of Nilsson *et al.*[8] using the nuclear deformations calculated by Möller and Nix.[9] More recent predictions for the proton levels in this region (Fig. 1 of Ref. 10) also support the $\frac{7}{2}^-$[523] assignment for the 67th proton.

In a similar experiment at the $A = 171$ mass chain, a 128-s tape cycle time was used to determine the half-life and the decay scheme of ^{171}Ho. Rykaczewski *et al.*[11] first

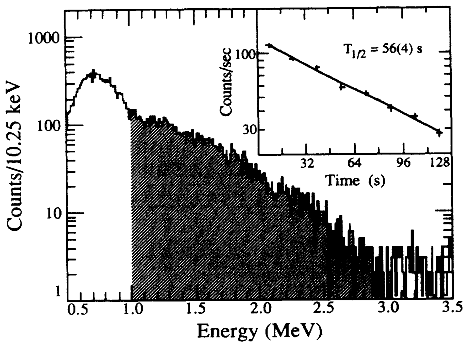

FIG. 5. β particle spectrum measured with the β telescope for the $A=171$ mass chain. The inset shows the single-component background-subtracted decay of the β intensity between 1.0 and 3.0 MeV (shaded portion of the spectrum).

identified this isotope by measuring 47(5) s Er K x rays in coincidence with electrons in plastic scintillators. We were able to confirm their findings by measuring Er K x-ray coincident β^- particles with energies up to ~ 2.5 MeV.[2] In this experiment, short-lived, high-energy β^- particles (1.0–3.0 MeV), which extended beyond the β end points of the known $A=171$ isobars, were seen in the β telescope and found to decay with a half-life of 56(4) s. Figure 5 shows the β^- spectrum and the background-subtracted single-component decay curve for the β intensity between 1.0 and 3.0 MeV. A Fermi-Kurie analysis was performed on these β's, but no unambiguous β end point could be deduced. Table I lists the Er K x rays and fifteen γ rays assigned to the decay of ^{171}Ho with their measured relative intensities and γ-ray coincidences. These transitions were all short lived with an average half-life of 54(3) s and were in coincidence with β^- particles in the β telescope. The identification of the 199- and 279-keV γ rays presented difficulties due to interfering radiations induced at these energies by the neutron background. Analysis of the 358-keV γ ray was complicated by a sum peak from the 308-keV γ ray and the Tm K_α x rays in ^{171}Er decay.[12] The 61.2-keV γ ray could not be resolved in the singles spectra due to Lu K_β x rays at this energy, however, the 61.2-keV transition was detected in β-gated coincidence data where its intensity was determined relative to the 79-keV transition. The 61.2-keV transition was determined to be $M1$ from its measured K conversion coefficient. Six of the γ rays reported in Table I have been observed previously in the adopted level scheme for ^{171}Er.[13] Based on the past studies, coincidence and intensity information, we propose the partial ^{171}Ho decay scheme in Fig. 6.

The decay scheme is consistent with the absence of a unique β end point due to the many different β branches shown. The 199-keV level had a measured lifetime of 200(30) ns in good agreement with the previous result of 210(10) ns.[13] The placement of the 841-keV level is uncertain because of the possible reversal of the order of the 61- and 642-keV γ cascade and could alternatively be placed at 259.8 keV. There is no indication of direct β feeding to this level. The upper limit for β feeding to the 199-keV level is $\leq 2\%$, but because decay to this level would be second forbidden (unique), no β feeding to this level is proposed. The β intensities and logft limits listed in Fig. 6 were calculated assuming no ground-state feed-

TABLE I. γ-ray energies E_γ, intensities I_γ(rel), and γ-ray coincidences measured in the decay of ^{171}Ho.

E_γ (keV)	I_γ(rel)[a]	Coincident γ rays (X=Er K x rays)
48.2 Er $K_{\alpha 2}$	51(8)	X, (61), 199, 279, (454), (642), (708), (903), (907), (1687)
4.91 Er $K_{\alpha 1}$	106(7)	b
55.7 Er $K_\beta 1$	34(3)	X, 199, 279, (358), (454), (824)
61.2(5)	4(2)	X, 199, 642
79.1(1)	25(2)	X, 279, (454), (824), (1687)
198.6(1)	88(23)	X, 61, 642, 705, (708)
279.2(4)	60(9)	X, 79
358.3(3)	49(33)	X
453.8(3)	13(4)	X, 79
532.2(1)	58(4)	X
642.5(2)	39(5)	X, (61), 199
704.7(3)	27(5)	X, 199
708.5(1)	34(19)	X, 199
727.6(1)	44(5)	X
823.9(5)	30(6)	X, 79
903.3(4)	100(6)	c
907.2(2)	57(6)	(X)
1687.1(10)	25(8)	X, (79)

[a]Intensities are relative to 100 for the 903.3-keV γ transition.
[b]"Clean" coincidence gate could not be set due to interferences of Tm $K_{\alpha 2}$ x rays.
[c]No coincidences were observed.

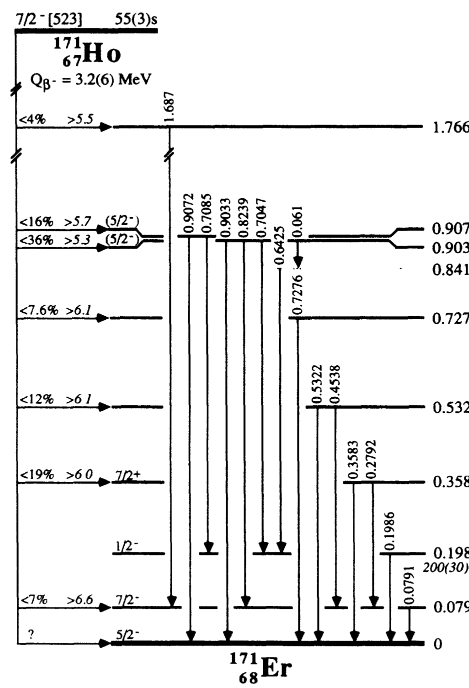

FIG. 6. Proposed decay scheme for ^{171}Ho. Energies are in MeV. The Q_β value is from this experiment. β branches and logft limits were calculated assuming no ground-state β branch.

ing. Since β transitions have been measured between the $\frac{7}{2}^-[523]$ proton and the $\frac{5}{2}^-[512]$ neutron states,[7] ground-state β feeding is expected in ^{171}Ho decay, but could not be determined. The spin and parity for the first four ^{171}Er levels listed in the decay scheme are from the adopted level scheme.[13] The proposed $\frac{5}{2}^-$ assignments for the 903- and 907-keV levels are the only assignments consistent with allowed Gamow-Teller β decay and the observed γ-ray decay pattern. The assignment of the ^{171}Ho parent state (the 67th proton) as $\frac{7}{2}^-[523]$ was discussed above in the ^{169}Dy decay. As discussed in Ref. 11, the decay of ^{171}Ho is expected to be dominated by a fast allowed unhindered[14] $\frac{7}{2}^-[523]$ to $\frac{5}{2}^-[523]$ transition. The most likely candidate for this $\frac{5}{2}^-[523]$ state is the 903-keV level which is close to the predicted[11] energy of 1.15 MeV. The logft value of 5.3 is, however, considerably slower than the corresponding transitions in ^{167}Ho and ^{169}Ho β^- decays (4.5 and 4.8, respectively).[7] (It should be pointed out that the logft limit has a large uncertainty due to the Q value.) The average predicted Q_β value for the decay of ^{171}Ho is $\sim$3.2 MeV.[6] A Fermi-Kurie analysis of β^- particles feeding the 903- and 907-keV levels yielded an end point of 2.3(6) MeV, consistent with the predicted Q value. A half-life of 55(3) s, calculated as the weighted average of all the γ and β decay information, is adopted for this isotope.

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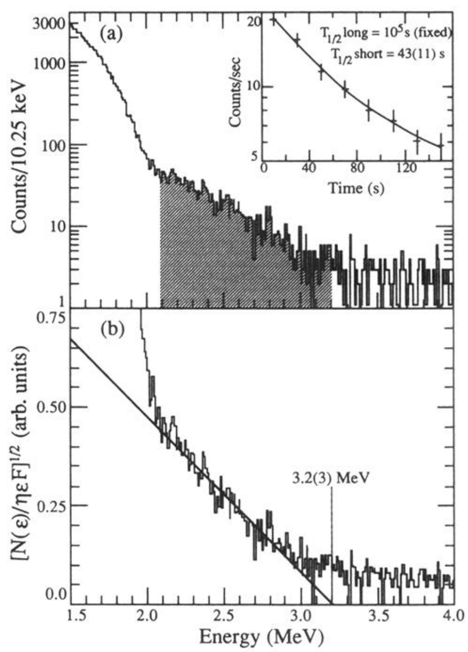

FIG. 1. β-decay data for the $A = 169$ mass chain; (a) β particle spectrum measured in the β telescope and (b) Fermi-Kurie plot and least-squares linear fit from 2.1 to 2.9 MeV resulting in a β end point of 3.2(3) MeV. The inset in (a) shows the two-component background-subtracted decay of the β intensity between 2.1 and 3.2 MeV (shaded portion of the spectrum).

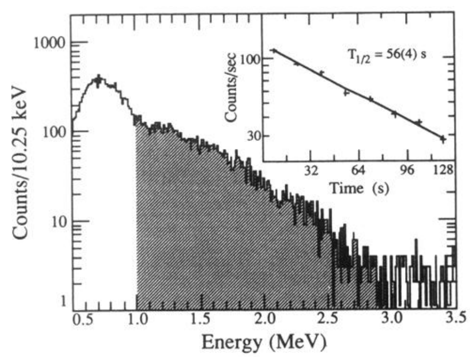

FIG. 5. β particle spectrum measured with the β telescope for the $A=171$ mass chain. The inset shows the single-component background-subtracted decay of the β intensity between 1.0 and 3.0 MeV (shaded portion of the spectrum).