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Decay studies of the neutron-rich isotopes ^{168}Dy and ^{168}Ho^{g} and the identification of the new isomer ^{168}Ho^{m}

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Multinucleon transfer reactions between ^{170}Er ions and ^{nat}W targets with on-line mass separation were used to produce neutron-rich $A=168$ isotopes. β and γ spectroscopy was used to study the decay of these activities. A new isomer of holmium, ^{168}Ho^{m}, was identified to decay by an isomeric transition with a half-life of 132(4) s. A decay scheme for the most neutron-rich $A=168$ isotope, 8.8(3)-min ^{168}Dy, was determined. Also, a new Q_{β^-} value of 2.93(3) MeV for the decay of 3.0-min ^{168}Ho^{g} has been obtained.

Studies of neutron-rich rare-earth nuclides with the On-line Apparatus for SuperHILAC Isotope Separation (OASIS) facility[1] at the Lawrence Berkeley Laboratory's (LBL) SuperHILAC using neutron-rich rare-earth beams have progressed over the last few years. Past studies characterized the new isotopes ^{169}Dy (Ref. 2) and ^{174}Er (Ref. 3) and deduced the decay scheme of ^{171}Ho.[2] The present experiment was performed to determine the decay scheme of ^{168}Dy. Gehrke *et al.*[4] previously measured an 8.5(5)-min half-life for ^{168}Dy and assigned five γ rays to this isotope but no decay scheme was constructed.

An 8.5-Mev/nucleon ^{170}Er beam, with 50–125 particle nA intensity, from the LBL SuperHILAC and ^{nat}W targets located inside the OASIS ion source were used to produce projectilelike neutron-rich lanthanides via multinucleon transfer reactions. Reaction products were surface ionized, mass analyzed, and the $A=168$ mass chain transported ionoptically to a shielded counting area. The $A=168$ activities were then collected on a fast-cycling tape system and transported, within 200 ms, to a detector array for β- and γ-ray spectroscopy. β particles and low-energy (10–400 keV) photons were detected with a telescope consisting of a 718-μm-thick Si detector and a planar hyperpure Ge (HPGe) detector which faced the radioactive layer of the tape, while a large solid angle ($\sim$35% of 4π) 1-mm thick plastic scintillator, for electron detection, and a 52% efficient Ge detector, for γ-ray detection, were located on the opposite side of the tape. A third 24% efficient Ge detector was located at 90° with respect to the other detectors $\sim$4.5 cm from the source. Singles data were acquired for all three Ge detectors. For half-life determinations, the HPGe and 52% Ge detector data were time resolved, with the tape cycles divided into eight equal time intervals. Coincidence events registered in the various detectors were recorded in an event-by-event mode.

A tape cycle time of 1024 s was used to optimize the yield of the 8.5-min ^{168}Dy activity and give adequate growth and decay statistics for the 3.0-min ^{168}Ho^{g} daughter.[5] All five γ rays previously assigned to ^{168}Dy decay (143, 192, 443, 487, and 630 keV) were observed to decay with the previously measured half-life.[4] Also, two new γ rays at 43.8 and 437.0 keV were found to decay with a similar half-life. A weighted average value of 8.8(3) min was calculated for the half-life of the seven γ rays. Inspection of the Ho $K\alpha_1$ and $K\alpha_2$ x rays, however, yielded two component decay curves (a short-lived component in addition to the 8.8-min ^{168}Dy) which are shown in Figs. 1(a) and 1(b).

The absolute decay rate of ^{168}Dy was determined by observing the growth and decay of its ^{168}Ho^{g} daughter γ rays. However, this was complicated by the short-lived activity (132-s ^{168}Ho^{m} discussed below) observed in the x-ray singles data (Fig. 1), which also decayed to ^{168}Ho^{g}. Figure 2 shows the decay data of the two strongest γ rays (741 and 821 keV) in the decay of ^{168}Ho^{g} during the 1024-s experiment. Decay curve fits for the two parents, ^{168}Dy (8.8 min) and ^{168}Ho^{m} (132 s), feeding one

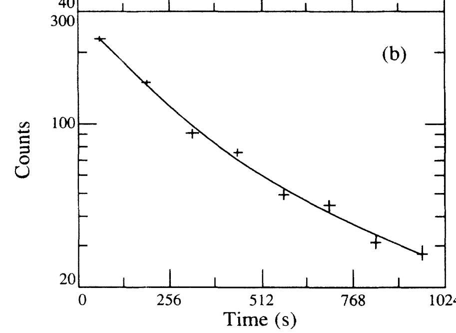

FIG. 1. Two-component decay curve fits to the Ho x-ray data for the 1024-s experiment; (a) Ho $K\alpha_1$ (47.5 keV), and (b) Ho $K\alpha_2$ (46.6 keV) with the long-lived component of each decay fixed at 8.8 min. The resulting short-lived components are 134(8) and 130(11) s for (a) and (b), respectively. Vertical bars on data points (shown as crosses) are indicative of the uncertainty in the activity at each point.

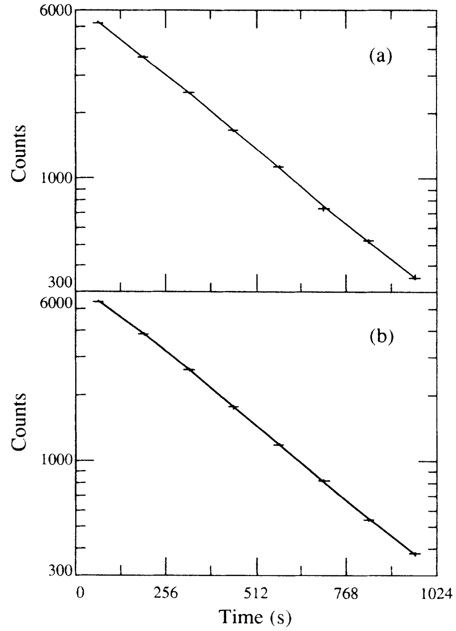

FIG. 2. Calculated growth and decay curve fits for ^{168}Dy and ^{168}Ho^m parents feeding the same daughter activity, 3.0-min ^{168}Ho^g, for the 1024-s experiment; (a) 741-keV γ-ray decay and (b) 821-keV γ-ray decay. All half-lives were held fixed with the two parents at 8.8 min and 132 s, respectively, and their daughter at 3.0 min.

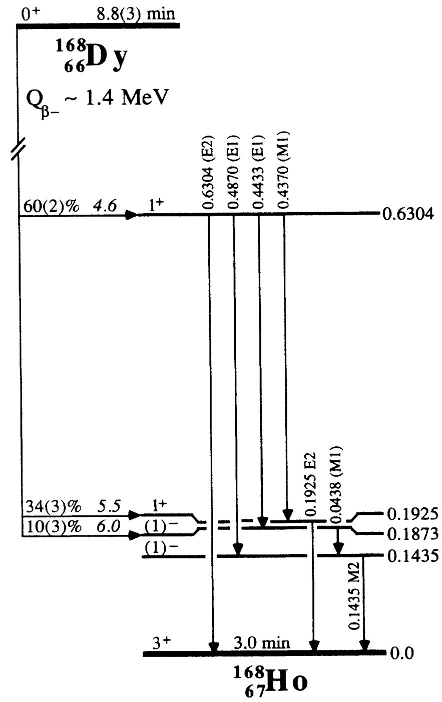

FIG. 3. Proposed decay scheme for the decay of 8.8-min ^{168}Dy. Energies are in MeV. The Q_{β^-} value is taken from Ref. 7. Logft's are in italics following the β^- intensities. The spin and parity assignments are discussed in the text.

daughter activity, ^{168}Ho^g, are shown in Fig. 2, with all half-lives held fixed. The decay intensity of the 8.8-min parent ^{168}Dy was integrated over the counting interval and corrected for the known emission probabilities[6] of the 741- and 821-keV γ rays from ^{168}Ho^g, 0.359(8) and 0.347(8), respectively, to yield the total ^{168}Dy decay intensity. An emission probability per β decay of 0.225(16) was determined for the 487.0-keV γ ray from ^{168}Dy in good agreement with the previous value of 0.22(4).[4]

Table I lists the energies, absolute intensities, multipolarities, total conversion coefficients, and γ-ray coincidences for the transitions assigned to the decay of 8.8-min ^{168}Dy. The Ho $K\alpha$ x-ray intensities, also given in Table I, were determined by integrating the long-lived component of the decay curves in Fig. 1. All γ and Ho $K\alpha$ x rays were seen in coincidence with β^- particles in the β telescope or the plastic scintillator. The multipolarity of the 43.8-keV transition could not be measured directly since the Ho L x-ray energies were too low to be observed, but was inferred from intensity balances in the decay scheme proposed in Fig. 3. The Q_{β^-} value was predicted to be ~1.4 MeV using the atomic mass predictions compiled by Haustein.[7] The 192.5-keV level was measured to have a half-life of 108(11) ns using the timing informa-

TABLE I. γ-ray energies E_γ, absolute intensities I_γ, multipolarities M, theoretical total conversion coefficients α, and γ coincidences in the decay of ^{168}Dy.

E_γ (keV)	I_γ (abs.)	M[a]	α	Coincident γ rays[b]
43.8(2)	0.044(4)	(M1)	4.90	X, (143), 443
46.6 Ho $K\alpha_2$	0.122(14)			43.8, X, (143), 443, 487
47.5 Ho $K\alpha_1$	0.213(23)			c
143.5(2)	0.065(5)	M2	6.72	43.8, 487
192.5(2)	0.328(20)	E2	0.279	(X), 437
437.0(7)	0.085(11)	(M1)	0.0465	X, 192
443.3(2)	0.155(11)	(E1)	0.00703	43.8, X, (143)
487.0(2)	0.225(16)	(E1)	0.00569	X, (143)
630.4(3)	0.136(11)	(E2)	0.00897	d

[a]Parentheses indicate the multipolarity was not measured but inferred from intensity balances or spin assignments of the decay scheme.
[b]X = Ho K x rays. Parentheses indicate a weak coincidence.
[c]Due to Er $K\alpha_2$ interferences, no clean coincidence gate could be set.
[d]No coincident γ rays were observed.

tion between β^- particles and 192.5-keV γ rays. The half-life of this level from the single-particle model for an $E2$ transition and corrected for internal conversion is expected to be 30 ns. The half-life of the 143.5-keV level was longer than the resolving time (1.5 μs) of the time-to-amplitude converter spectrum, and is estimated, from intensity ratios of the coincidence and singles data, to be > 4 μs, consistent with the single-particle estimate of 2 μs. The half-lives of all other levels were found to be < 5 ns.

The ^{168}Ho ground-state spin and parity have been assigned as 3^+.[8] The 1^+ spin and parity of the 193- and 630-keV levels are the only assignments consistent with both the measured low logft values and ground-state γ transitions. The negative parity assignments of the 143- and 187-keV levels are based on the γ multipolarity assignments and the weak β branches. Either a 0^- or 1^- assignment is compatible with the γ-ray deexcitation of the 187-keV level, but a 0^- assignment is inconsistent with log$ft > 7$ measured for other $0^+ \rightarrow 0^-$ β^- transitions in this region.[9] In ^{166}Dy decay, a log$ft = 5.9$ has been measured for a $0^+ \rightarrow 1^-$ β^- branch.[9] We therefore propose a 1^- assignment for the 187-keV level. Ground-state β feeding could be estimated as less than 4%(2σ) from the measured transition intensity feeding into the ground state $[I_{\gamma+CE} = 1.06(5)]$. β feeding to the 143-keV level had a measured upper limit of $\leq 2(5)$%; however, with all of the β intensity already accounted for and the large relative error on this β branch, no feeding to this level is proposed.

To identify the short-lived activity seen in both the Ho $K\alpha$ x rays (Fig. 1) and the 3.0-min ^{168}Ho growth and decay, an experiment with a shorter tape cycle of 512 s was carried out. The Ho $K\alpha_1$ and $K\alpha_2$ x rays again exhibited two-component decay curves and a weighted average of 132(4) s was obtained for the half-life of the short-lived component from both the 512- and 1024-s experiments. However, no γ rays could be found that decayed with this half-life. Possible explanations of this activity are a new ^{168}Dy isomer, which predominantly β^- decays (^{168}Dy decay showed no growth and decay behavior) through a highly converted γ transition, or a new ^{168}Ho^m isomer decaying by a highly converted isomeric transition (IT). Since long-lived isomers of even-even isotopes are not expected in this region, the activity is assigned to the new isomer ^{168}Ho^m with a half-life of 132(4) s.

The total IT intensity of this new isomer was determined by analyzing the growth and decay curves of its daughter's 741- and 821-keV γ rays (similar to ^{168}Dy decay). An absolute Ho K x-ray intensity of 0.133(10) per IT decay was measured. For K-shell internal conversion, a γ transition of ≥ 56 keV is required. To obtain a 132-s half-life, an $E3$ or $M3$ γ transition is necessary, but the $E3$ transition is ruled out due to the K x-ray intensity and absence of the γ-ray detection. An $M3$ transition at 59 keV would have the correct K x-ray intensity and a γ-ray intensity per IT decay of 4.02×10^{-4}, which is below our detection limit. For $M3$ transitions with energies near the K binding energy, the K x-ray intensity is very sensitive to transition energy, but is essentially linearly dependent on energy near 60 keV. Assuming pure $M3$ multipolarity, we can estimate the energy of the unobserved transition to be 59(1) keV with a $B(M3) = 0.088$.

The isotope ^{172}Lu, with four more protons than ^{168}Ho, also has an isomer that decays via a 3.7-min $M3$ IT at 41.9 keV (Ref. 9) with a similar $B(M3) = 0.053$. The spins of ^{172}Lu^g (4^-) and ^{172}Lu^m (1^-) were proposed to

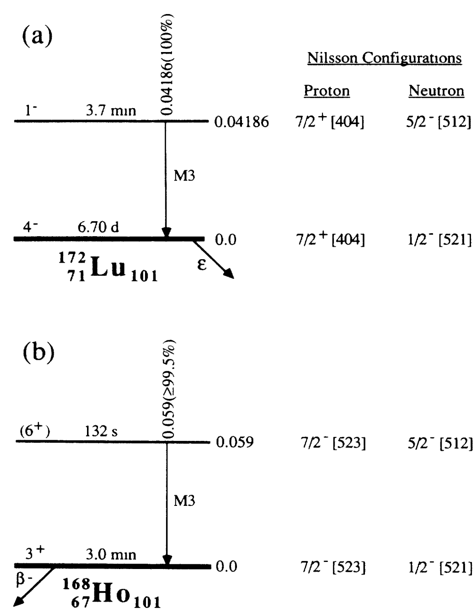

FIG. 4. Partial level schemes of $N = 101$ isomers and their Nilsson model proton and neutron configurations; (a) ^{172}Lu^g and ^{172}Lu^m, and (b) ^{168}Ho^g and proposed ^{168}Ho^m. Energies are in MeV.

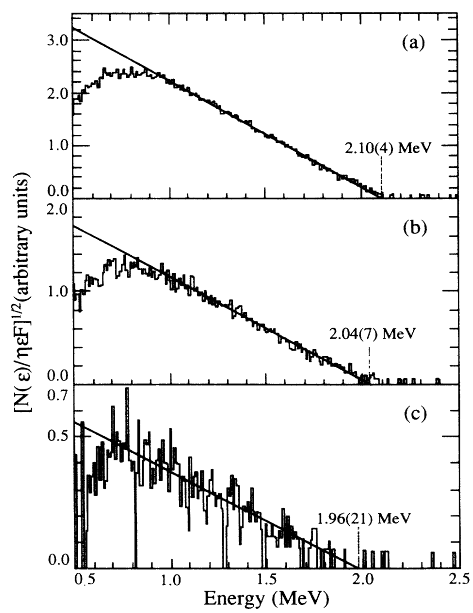

FIG. 5. Fermi-Kurie plots of γ-gated, background-subtracted β-particle spectra for ^{168}Ho^g β^- decays to levels in ^{168}Er; (a) 821-keV level, (b) 896-keV level, and (c) 995-keV level. The fitting intervals used in the least-squares linear fits were (a) 1.0–2.0 MeV, (b) 1.0–1.9 MeV, and (c) 0.8–1.5 MeV.

result from the coupling of the $\frac{7}{2}^+$[404] proton state and the $\frac{1}{2}^-$[521] (ground) and $\frac{5}{2}^-$[512] (first excited) neutron states, respectively,[10] as shown in Fig. 4(a). The ^{168}Ho ground-state spin and parity of 3^+ presumably results from the coupling of the $\frac{7}{2}^-$[523] proton state and the $\frac{1}{2}^-$[521] neutron state. Assuming a similar coupling scheme as in ^{172}Lu, ^{168}Ho^m would then result from the coupling of the $\frac{7}{2}^-$[523] proton state and the $\frac{5}{2}^-$[512] neutron state, shown in Fig. 4(b). This is consistent with the assignment of 6^+ from the $M3$ transition and thus the isomer would not be populated by ^{168}Dy decay. A similar 6^+ coupling was also proposed as the ground-state configuration of ^{170}Ho.[11,12] We, therefore, assign a 6^+ spin and parity for the 132(4)-s ^{168}Ho^m isomer at 59(1) keV above the 3.0-min ^{168}Ho ground state. This activity decays predominantly (>99.5%) by IT decay since there was no evidence for β^- decay which would have been seen as an enhancement in the ^{168}Er 6^+ to 4^+ transition (284 keV) intensity.[6] The proposed partial decay scheme for ^{168}Ho^m is shown in Fig. 4(b).

The Q_{β^-} value for ^{168}Ho^g decay has been reported as 2.74(10) MeV from end point measurements of β^- particles (measured in a 5.08 cm diam by 1.27 cm plastic detector) coincident with 80-, 741-, and 821-keV γ rays from ^{168}Ho^g decay.[5] In our experiment, considerable statistics were acquired for the β^- decay of ^{168}Ho^g. γ-gated, background-subtracted β spectra, measured in the β telescope, were acquired in coincidence with γ rays deexciting the 821-, 896-, and 995-keV levels in ^{168}Er. Fermi-Kurie plots were made for each spectrum and the end points were determined using least-squares linear fits. (Further details of the β detector calibration and analysis are given in Ref. 2.) Figures 5(a)–5(c) show the Fermi-Kurie plots and Table II lists the results for this analysis and the resulting Q values, from which a weighted average Q_{β^-} value of 2.93(3) MeV for the decay of ^{168}Ho^g was calculated, which is slightly higher than the previous value.

TABLE II. Level energies, γ-ray gates, β^- end points, and Q_{β^-} values for ^{168}Ho^g decay.

Level energy (keV)	Gate energies[a] (keV)	End point energy (MeV)	Q_{β^-} (MeV)
821.1	741, 821	2.10(4)	2.92(4)
895.7	632, 816	2.04(7)	2.94(8)
994.7	731, 915	1.96(21)	2.96(21)

[a]Coincidence gates summed for the indicated transition energies.

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