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Beta decay of ^{154}Lu and ^{154}Yb

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Using mass-separated sources, the β-decay properties of ^{154}Lu and ^{154}Yb were investigated. Limits of ^{154}Lu decay to the first 8^+ and 6^+ levels in ^{154}Yb suggest a 7^+ spin for the odd-odd parent; also delayed proton emission and an indication of delayed α-particle emission were observed to follow ^{154}Lu β decay. The β-decay branch of the α-emitting nucleus ^{154}Yb was identified for the first time by the observation of one intense 133.2-keV γ ray. This transition deexcites a 1^+ 133.2-keV level in ^{154}Tm which is fed by an allowed $0^+ \rightarrow 1^+ \beta$ transition with a logft value of 3.6 ± 0.3.

The decay of ^{154}Lu to ^{154}Yb has been studied previously by Rathke[1] and by Habenicht *et al.*;[2] Rathke[1] has also performed in-beam γ-ray measurements in an investigation of ^{154}Yb levels. The isotope ^{154}Lu was also produced in a study of ^{154}Yb α-particle emission.[3,4] The present investigation of ^{154}Lu and ^{154}Yb decay was done at the OASIS mass-separator facility[5] on-line at the Lawrence Berkeley Laboratory SuperHILAC. It extends our systematic studies[6] of $N \leq 82$ nuclei to the region above the $N = 82$ shell.

Molybdenum foils 2.08 mg/cm^2 and 1.85 mg/cm^2 thick, enriched to 92% in ^{94}Mo and 97% in ^{92}Mo, respectively, were bombarded with 285-MeV ^{64}Zn ions. Reaction products were mass separated and $A = 154$ isobars were transported ionoptically to a shielded counting area located 4 m above the separator. There, the radioactive ions were collected on a fast-cycling tape system and transported within 65 ms to a detector array for charged particle and photon spectroscopy. A $\Delta E - E$ particle telescope and a planar hyperpure Ge 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% detector was placed at 90° relative to the other detectors, about 4.5 cm from the radioactive source. Coincidence events registered in the various detectors were recorded in an event-by-event mode. Singles spectra were acquired from all three γ-ray detectors. A time resolved multispectrum mode was used for the singles spectra accumulated in the 52% Ge and in the hyperpure Ge detector where the 2.56 s tape cycle was divided into eight equal time intervals for half-life determinations.

Electron capture (EC) intensities were derived from the K x-ray intensities corrected for fluorescence yields ω_K, EC(K)/EC(tot) ratios, and internal conversion. For ^{154}Lu it was assumed that the total β intensity is equal to the 821.3-keV $(2^+ \rightarrow 0^+)$ transition intensity in the daughter ^{154}Yb because of the high spin of the parent ^{154}Lu. The positron intensity for ^{154}Lu decay was calculated by subtracting the EC intensity from the 821.3-keV γ-transition intensity. This calculated β^+ intensity for ^{154}Lu decay was then fixed in a multicomponent time analysis of the annihilation radiation peak to extract the positron intensity for ^{154}Yb decay. Corrections of 7% and 20% due to annihilation in flight and summing, respectively, were made, when determining these intensities.

Four γ rays, listed in Table I, were assigned to ^{154}Lu β

TABLE I. Energies, γ-ray, and conversion-electron intensities in ^{154}Lu β decay.

E_γ (keV)	I_γ (relative)	I_{CE} (total)[a]
96.6 ± 0.2	12 ± 3	43 ± 10
433.6 ± 0.2	83 ± 2	2.2 ± 0.1
694.7 ± 0.2	97 ± 2	0.79 ± 0.01
821.3 ± 0.2	100	0.57 ± 0.01

[a]Conversion coefficients are calculated (Ref. 7) assuming an $E2$ multipolarity.

decay. A half-life of 1.16 ± 0.05 s was deduced for ^{154}Lu from the decay curves of the Yb K x rays and the four γ rays. Our proposed decay scheme for ^{154}Lu is shown in Fig. 1, where the spin assignments of levels in ^{154}Yb are based on the systematics[1,2] of even-even $N=84$ nuclei in this mass region. The first 8^+ level in ^{154}Yb ($N=84$) is about 226 keV lower than the same state in the more neutron rich ^{156}Yb ($N=86$). Suppressed energies for the first 8^+ levels have also been observed at $N=84$ in even-even Dy and Er isotopes between $N=82$ and $N=86$. This indicates a possible two-particle structure for the 8^+ levels in the $N=84$ nuclei. The 96.6-keV $E2$ transition in ^{154}Yb is not much enhanced and is consistent with the two-particle structure for the 8^+ level. An $E2$ multipolarity for the 96.6-keV transition was assigned based on the comparison of the theoretical K-conversion coefficient[7] $\alpha_K(E2)=1.1$ with the experimental value of $\alpha_K=1.3 \pm 0.3$, derived from the intensity ratio of Yb K x rays to 96.6-keV γ rays measured in coincidence with positrons. A 10% correction for the Yb K x-ray intensity was made to take into account conversions of other transitions following ^{154}Lu decay.

The low logft limits to the 8^+ and 6^+ levels (Fig. 1) suggest allowed β transitions. Because the parent state in odd-odd ^{154}Lu has a two-particle structure, low logft value limits (Fig. 1) suggest similar structure for the 6^+ and 8^+ levels in ^{154}Yb. It is, however, possible that these levels are also populated by unobserved γ transitions from higher-lying levels which may increase the logft values.

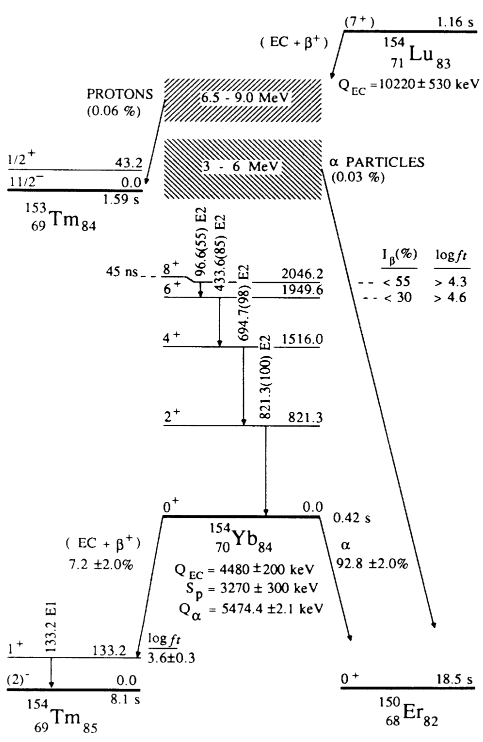

FIG. 1. Decay schemes of ^{154}Lu and ^{154}Yb. Decay energies ($Q_{\rm EC}$), and proton and α-particle binding energies are from Ref. 12. The $1/2^+$-$11/2^-$ level energy difference in ^{153}Tm was taken from Ref. 11. All energies are expressed in keV.

The measured EC/β^+ intensity ratio of 0.30 ± 0.10 does indicate feeding to levels at higher excitation energies since the expected EC/β^+ ratio for β transitions to the 6^+ and 8^+ states is about 0.10. However, the 96.6-keV transition has only 55% of the 821.3-keV transition intensity. We thus conclude that the 8^+ and 6^+ levels do receive strong direct β feedings, implying a spin assignment of 7^+ for ^{154}Lu parent (Fig. 1). This spin value differs from the systematic 9^+ trend in Ref. 2. The 9^+ spin and parity arise from the strongly attractive two-particle coupling of the $(\pi h_{11/2} \nu f_{7/2})$ configuration.[8] At $Z=70$, however, the proton $h_{11/2}$ orbital is about 50% filled and the strong two-particle coupling may vanish. Indications of this effect at $Z=70$ have been observed in high-spin isomer studies of even-odd $N=83$ nuclei,[8] and in $B(E2;\ 10^+ \rightarrow 8^+)$ values in the $N=82$ isotones.[9]

Our results contradict one major point in the level scheme reported by Rathke,[1] i.e., the 96.6-keV transition was placed between levels at 3607.2 and 3510.2 keV, while an unobserved isometric (51 ± 5-ns) transition with an estimated energy of <100 keV was suggested to deexcitate the 8^+ state to the 6^+ level. Conversely, we observe all four γ transitions in prompt coincidence (<30 ns) with each other and therefore assign the 96.6-keV transition to deexcitate the 8^+ level. We do observe a 45 ± 10-ns lifetime in our experiments; we place this delay with the 2046.2-keV 8^+ level due to the fact that in a time gate (30-100 ns delay range) only the Yb K x rays and annihilation radiation were observed in coincidence with the 96.6-, 433.6-, 694.7-, and 821.3-keV γ rays. In the level systematics of even-even $N=84$ Dy and Er isotopes the 10^+ states lie well above the 8^+ levels, and in ^{150}Dy a 1.1-ns isomeric 10^+ level has been observed,[10] which would suggest a very short lifetime for the corresponding 10^+ level in ^{154}Yb. Rathke[1] reported a possible 10^+ level 868.3 keV above the 8^+ level. Because of the low energy of 96.6 keV for the $8^+ \rightarrow 6^+$ transition in ^{154}Yb and the observed strong intensity of the delayed (30-100 ns) coincidence activity for the 96.6-keV γ ray, we propose that the observed isomeric level (45 ns) is the first 8^+ state in ^{154}Yb. This agrees with the suggested isomeric 8^+ level assignment of ^{154}Yb reported by Rathke.[1] Similar isomeric 8^+ levels have also been observed in the $N=82$ nuclei ^{150}Er and ^{148}Dy with 20- and 65-ns lifetimes,[10] respectively.

Beta-delayed proton emission has recently been reported for a rare earth nuclide with $N>82$, namely, ^{153}Yb.[11] The $Q_{\rm EC}-S_p=6.95$ MeV energy window[12] for ^{154}Lu indicates that delayed proton emission is a possible decay mode. Furthermore, the ground state of ^{154}Yb is known to decay predominantly via α-particle decay with $Q_\alpha=5.474$ MeV,[12] which suggests that ^{154}Lu could also exhibit β-delayed α-particle emission as well. We carried out a careful analysis of the $\Delta E-E$ particle telescope data, which were dominated by $\sim 2\times 10^5$ events from the ground state α decay of ^{154}Yb. Fifteen proton events were observed with energies of 3.2–5.7 MeV corresponding to an excitation energy region of 6.5–9.0 MeV in ^{154}Yb (proton emission to the ground state of ^{153}Tm was assumed), and a proton branching ratio of $\sim 6\times 10^{-4}$ was deduced for ^{154}Lu assuming that the 821.3-keV γ-transition intensity represents 100% of all β-decay events. Since no K x rays were observed in coincidence with protons due to the small number of events, the atomic number of the proton precursor could not be confirmed directly. However, it is unlikely that ^{154}Yb is a strong proton precursor since its $Q_{EC}-S_p$ value is only 3.16 MeV,[12] and ^{154}Hf has an insignificant cross section and a very low yield in the surface ionization source of mass separator.[5] Eight possible α particle events with energies of 8.5–11.5 MeV corresponding to an excitation energy region of 3–6 MeV in ^{154}Yb were observed (α-particle emission to the ground state of ^{150}Er was assumed), and an α-branching ratio of $\sim 3\times 10^{-4}$ was deduced for ^{154}Lu. The nuclidic assignment of this delayed α activity is based on energetics[12] (Fig. 1). In a previous $A=153$ mass experiment[11] with the identical detector arrangement we recorded about 40 times more direct α events than at $A=154$, but we did not identify any β-delayed α particles. Further experiments to improve the proton and α-particle statistics for ^{154}Lu decay are, however, needed to confirm these preliminary results. We note that the time distribution of the β-delayed α particle and proton events is compatible with a half-life in the range of 1–2 s, i.e., a value consistent with decay from ^{154}Lu.

The β-delayed proton and α-particle decay properties of ^{154}Lu were analyzed within the framework of the statistical model (SM) outlined in Ref. 6. These calculations reproduce the observed energy ranges of both the β-delayed proton and α-particle spectra; reasonable variations in the β-strength function distribution and other model parameters give similar predicted energies. On the other hand, the absolute particle decay branches and their ratio were found to be very sensitive to the choice of model parameters, especially the parent spin, the β-strength function, and the partial level widths in the intermediate nucleus. Among the three possible choices for the parent J^π (7^+, 8^+, and 9^+),[2,13] spin 7^+ gave better overall agreement with the experimental results. Using a constant β-strength function, the calculations gave delayed proton and α branches of $\sim 2\times 10^{-5}$ and $\sim 8\times 10^{-7}$, respectively (with $J^\pi=7^+$), and a total EC/β^+ ratio consistent with the experimental value. By choosing a different β-strength function with concentration of the strength in the energy regions of observed proton emission 7–8 MeV and of α and γ emission 2–4 MeV (in a 4:1 ratio), it was possible to reproduce the measured delayed proton branch and, to a lesser extent, the delayed α branch without significantly altering the calculated EC/β^+ ratio. It is to be noted, however, that our SM calculation is expected to underestimate the delayed α branch for the following reasons. First, since there are no high-spin levels below about 2 MeV in ^{154}Yb, the γ transitions from possible α-emitting high-spin levels in the region of 3–6 MeV will be limited to populate the excitation energy region above ~ 2 MeV. Consequently, the relative gamma decay widths of these states are expected to be significantly smaller than those in our SM calculations.[6] In addition, γ feeding from higher excitation (7–9 MeV) levels to possible α-emitting intermediate levels (3–6 MeV), not taken into account in our model calculation, may become important in ^{154}Yb also due to the lack of low-lying high-spin levels. Finally, the SM is strictly valid only at high excitation energies in the intermediate nucleus where level densities are sufficiently high. At low excitation energies, reduced α-decay level widths may be substantially larger than those calculated with the SM. The ground state reduced α width of ^{154}Yb, derived from the measured half-life, is more than a factor of 100 larger than the values used for excited states in our model calculations. We conclude that the results from the SM calculations of delayed proton emission are in reasonably good agreement with experiment, and they do not rule out a competing delayed α branch.

This is the first investigation to identify the ^{154}Yb β-decay branch. In addition to thulium K x rays, one strong γ ray, 133.2 ± 0.2 keV, with a half-life of 0.42 ± 0.05 s was observed, and the same half-life was measured for ^{154}Yb α decay. A multipolarity of $E1$ for the 133.2-keV transition was assigned based on the comparison of the theoretical K-conversion coefficient[7] $\alpha_K(E1)=0.13$ to the experimental value of 0.11 ± 0.04, calculated from the intensity ratio of Tm K x rays to 133.2-keV γ rays measured in coincidence with positrons. The intensity of the 133.2-keV transition accounts for $(75\pm 15)\%$ of the total β-decay strength, indicating that there may be other weak γ rays which we do not observe. Indeed, the measured EC/β^+ intensity ratio of 1.10 ± 0.25 compared to the expected value of 0.85 for β feeding to the 133.2-keV level may indicate, within the uncertainty of Q_{EC}, that there is some unobserved β strength above the 133.2-keV level. Nevertheless, the primary β-decay pattern of ^{154}Yb appears to be similar to that reported (see, e.g., Refs. 14 and 15) for neighboring even-even nuclei, where much of the decay proceeds to a 1^+ level followed by an $E1$ transition to a 2^- ground state (or low-lying isomer). Indeed, we deduce that the β decay to this proposed 133.2-keV level in ^{154}Tm has a logft value of 3.6 ± 0.3, a rate which is typical for $0^+\to 1^+$ β transitions. As shown in Fig. 2, the energy of the 133.2-keV level fits well into the existing systematics for these 1^+ states in odd-odd Tb, Ho, and Tm nuclei with $N=83$, 85, and 87. In Refs. 14 and 15

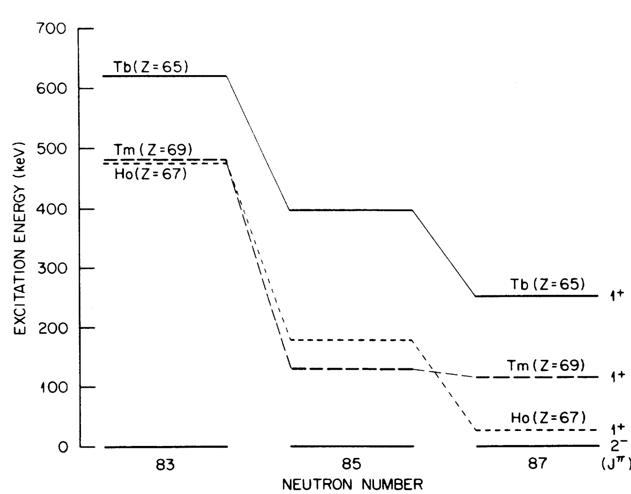

FIG. 2. Systematics of 1^+ levels in odd-odd Tb, Tm, and Ho nuclides with neutron numbers $N=83$, 85, and 87.

there is a discussion of possible configurations for these low-lying 1^+ and 2^- levels. We conclude by noting that our measured β- and α-decay branching ratios of $(7.2\pm2.0)\%$ and $(92.8\pm2.0)\%$, respectively, for the ^{154}Yb ground state decay are in agreement with the results of $(7\pm2)\%$ and $(93\pm2)\%$ reported by Hofmann *et al.*;[4] values they inferred from the observed α-particle intensities of ^{158}Hf and of ^{154}Yb present in the same radioactive source. Both sets of results differ from the adopted[13] estimates of 2% and 98% for the ^{154}Yb β- and α-branches, respectively.

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