Decay of 7-min ^{168}Lu and Levels of ^{168}Yb

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New data for the 7-min activity of ^{168}Lu are presented and combined with recent data on the levels of ^{168}Yb to assign the following levels (energies and spins) in ^{168}Yb populated by the decay of 7-min ^{168}Lu: 87.5 keV, 2+0 (ground-state rotational); 986 keV, 2+2 (γ-vibrational); 1233 keV, 2+0 (β-vibrational); 1410 keV, (1−0?, octupole vibrational?); 1550 keV (?); 2002 keV, 2±; and 2127 keV, 1±, or 2195 keV, 2±. The spin of ^{168}Lu is probably 1− or 2+. The 2-h activity of ^{168}Lu may also be created by the 6-MeV proton bombardment of ^{168}Yb. The upper limit for positrons in the 7-min ^{168}Lu decay can be 20 or 30%, rather than the originally reported 1%.

THE existence of a 7-min ^{168}Lu activity was first reported in 1960.[1] Shortly thereafter, Grigor'ev *et al.*[2] reported finding a series of conversion electron lines corresponding to an 87.5-keV transition in ytterbium with a half-life of 2 h which they assigned to ^{168}Lu, concluding that the probably electric dipole transition was the same one observed as an 87±1-keV γ ray in the 7-min activity. They attributed the two different half-lives to isomeric states in ^{168}Lu with probable spins of 2− and 7−. They reported that no positions were observed in the 2-h activity and reported no other transitions in the conversion electron spectrum. At about the same time, Merz and Caretto[3] reported the isolation of the 7-min activity from a 22-min parent hafnium activity which they assigned to ^{168}Hf. They reported the same γ rays in the 7-min activity as were previously reported,[1] plus others at 223 and 710 keV. They further reported the probable presence in the 7-min decay of a positron of 1.20±0.05 MeV end-point energy and an electron capture to positron decay ratio of about 8. We had originally reported[1] that if any positron decay existed in the 7-min activity, it comprised less than 1%. The ^{168}Lu activities reported in the three investigations mentioned were produced in three different ways: 6-MeV proton bombardment of ^{168}Yb enriched Yb_2O_3,[1] spallation of Ta by 660-MeV protons,[2] and spallation of Ta by 300- to 400-MeV protons.[3] A recent investigation of the reaction products from 12-MeV deuteron bombardment of the enriched stable isotopes of ytterbium by Burke and Elbek[4] has produced evidence for the assignment of a number of levels in ^{168}Yb.

Further study of the γ-ray spectrum of the activity produced by 6-MeV proton bombardment of $^{168}Yb_2O_3$ resulted in the observation of the new γ rays in the 7-min ^{168}Lu activity shown in Table I, a possible correction to the upper limit for the intensity of positrons in the 7-min activity originally reported in Ref. 1, and the possible observation of the 2-h ^{168}Lu activity.

When rare-earth oxides (Yb_2O_3 in this case) are bombarded with 6-MeV protons, in addition to the rare-earth activities produced, some 1.9-h ^{18}F activity is created by a (p, n) reaction with the small quantity of ^{18}O in the oxide. This nuclide decays solely by positron emission, creating in addition to particle radiation, a 511-keV annihilation radiation peak and some bremsstrahlung. The presence of this activity makes the certain identification of any other ~2-h activity and the existence of any other weak positron activity (of energy less than about 2 MeV and half-life less than 2 h) difficult in samples made in this manner.

A careful examination of the activity resulting from the bombardment of $^{168}Yb_2O_3$ by 6-MeV protons showed a 2-h component in the decay of both the 87.5-keV γ ray and the K x ray following the decay of the 7-min activity. The measured half-life values in this case were 2.3 h for the K x ray and 2.17 h for the 87.5-keV transition; a value of about 2.2±0.2 h can be assigned to this activity, in agreement with the 2.15±0.2 h value of Grigor'ev *et al.*[2] A more accurate value cannot be quoted because of the interference from the 1.9-h ^{18}F activity. No other γ rays which could be assigned to this activity were observed with a 2-h half-life and an intensity greater than about 20% of the intensity of the 87.5-keV γ ray. The measured ratio of the number of Yb K x rays to 87.5-keV γ rays in the apparent 2-h activity was 1.2±0.2 which is low when K conversion of the $E2$ 87.5-keV transition is considered. A determination of the presence of positron radiation (by either particle or annihilation radiation) in the 2-h ^{168}Lu activity made by this technique could not be made because of the presence of the 1.9-h positron of ^{18}F; Grigor'ev *et al.*[2] report no positron.

A further examination of the decay of the 511-keV annihilation radiation resulting from the 6-MeV proton bombardment of $^{168}Yb_2O_3$, starting 11 min after the bombardment ceased, has shown no definite 7-min component. Subtraction of the 1.9-h decay from the composite curve resulted in a decay line with a half-life of about 14 min. If this is the positron reported by Merz and Caretto[3] and is associated with the 7-min ^{168}Lu decay, then its decay is apparently being distorted by the 1.9-h ^{18}F which was not present in their sample. If it is not, then the positron activity in the 7-min ^{168}Lu activity is no more than was originally reported.[1]

[1] R. G. Wilson, Phys. Rev. **118**, 227 (1960).
[2] E. P. Grigor'ev, K. Ya. Gromov, B. S. Dzhelepov, V. Zvol'ska, A. V. Zolotavin, M. Veis, and Wang Yung-yü, Dokl. Akad. Nauk SSSR **136**, 325 (1961) [English transl.: Soviet Phys.—Doklady **6**, 46 (1961)].
[3] E. R. Merz and A. A. Caretto, Phys. Rev. **122**, 1558 (1961).

TABLE I. Relative γ-ray intensities in the decay of 7-min ^{168}Lu.

Energy (keV)	Relative intensity[a]	Energy (keV)	Relative intensity
K x ray	100 (98)[b]	1325[c]	0.5
87.5	7.5 (49)[d]	1410	2.5
511(β^+)	$\leq$50 ($\leq$25)[e]	1465[c]	1.0
900	10	1805	0.4
987	13	1910[c]	0.4
1145[c]	0.6	2000[c]	0.4
1235[c]	0.4	2135[f]	1.4

[a] $\pm\sim$25% for $E<1000$ keV; $\pm\sim$50% for $E>1000$ keV.
[b] Corrected for fluorescence (+7) and K conversion of the 87.5-keV γ ray (−9).
[c] Probable γ-ray transitions.
[d] Corrected for internal conversion of an $E2$ transition (Ref. 2).
[e] Corrected for positron annihilation radiation.
[f] This γ ray is very wide in energy distribution and could be two with energies and intensities of about 2100 (0.9) and 2195 (0.5).

The γ-ray spectrum of the 7-min ^{168}Lu activity has been examined in more detail and compared for reproducibility in two separate samples made by proton bombardment. More high-energy γ rays are resolved than were originally reported,[1] as shown in Table I. The estimated intensities, corrected for peak area, peak amplitude, and crystal efficiency, are shown in the table. The probable errors in the intensities for the γ rays of energy greater than 1 MeV are about $\pm$50 and $\pm$25% for those under 1 MeV. The positron intensity is subject to additional uncertainty as described previously. The probable error limits in the energy of the γ rays greater than 1 MeV is about $\pm$1.5%. Using the value for relative positron intensity as determined from annihilation radiation, the ratio of electron capture to positron emission is 4 or more after correction of the K x-ray intensity for K conversion of the 87.5-keV γ ray. This is less than the value estimated by Merz and Caretto,[3] whose value is assumed to be better because of the absence of the ^{18}F positron.

TABLE II. Probable levels for the states of the 71st proton and the 97th neutron.

Nuclide	$\frac{7}{2}+$[404]	$\frac{9}{2}-$[514]
^{169}Lu	g.s.	...
^{171}Lu	g.s. (?)	(g.s.)
^{173}Lu	123 keV (g.s.)	g.s. (123 eV)
^{175}Lu	g.s.	396 keV
^{177}Lu	g.s.	147 keV
	$\frac{5}{2}-$[523]	$\frac{5}{2}+$[642]
^{161}Gd	g.s.	23 keV
^{163}Dy	g.s.	very near g.s.
^{165}Er	g.s.	47 keV
^{167}Yb	g.s.	...

A reexamination of the 7-min ^{168}Lu activity produced by the method of Ref. 1 shows no γ rays with energies of 0.71 and 0.22 MeV with an intensity greater than 10% of that of the 900-keV γ ray; a back-scatter peak from the higher-energy γ rays occurs at an energy just less than 0.22 MeV and the strong 0.74-MeV peak of ^{171}Lu appears in the spectrum as the 7-min activity decays, making observation of transitions of such energies difficult.

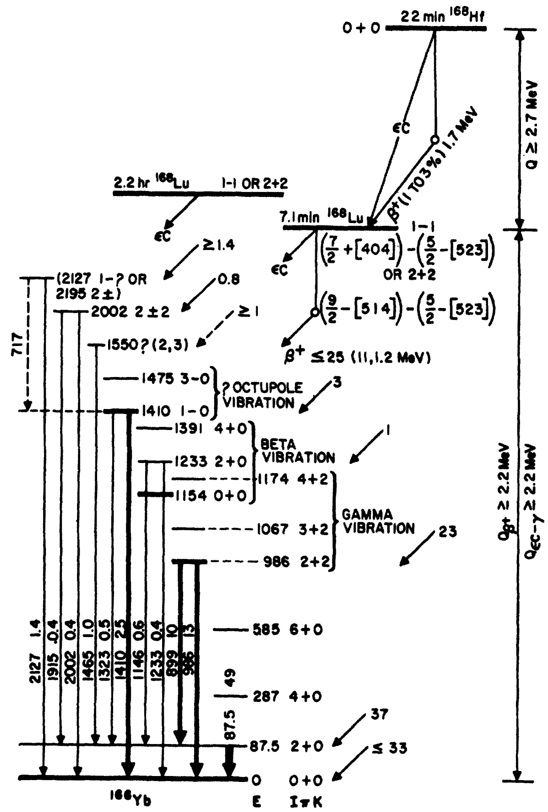

FIG. 1. Proposed decay scheme for neutron-deficient $A=168$.

Possible spin states for ^{168}Lu can be determined from the known states of the 71st proton and the 97th neutron. There are two possible states for each: the $\frac{7}{2}+$[404] or the $\frac{9}{2}-$[514] for the 71st proton and the $\frac{5}{2}-$[523] or the $\frac{5}{2}+$[642] for the 97th neutron. Probable assignments of these levels are shown in Table II. It is seen that the most likely states are the $\frac{7}{2}+$[404] and the $\frac{5}{2}-$[523]. Combination of these two yields 1− and 6− for ^{168}Lu, with 2+ and 7+ the next most likely (from substitution of the $\frac{9}{2}-$[514] for the 71st proton). The 7-min half-life of the ^{168}Lu activity and the occupation of only (or very predominantly) the 2+ level of the ground-state rotational band clearly indicates the choice of 1− (or 2+). The spin of the possible second ^{168}Lu activity (2 h) should be the other from the 1−, 2+ choice.

The energy difference between the 7-min ^{168}Lu state and the stable ^{168}Yb ground state can be estimated to be either 2.2 MeV or 3.2 MeV from the experimental observation[3] of a 1.2-MeV positron in the activity, depending upon whether the positron decay occurs to the ground-state band (0+ or 2+ level) or to the 986-keV (2+) level. If the spin of the 7-min ^{168}Lu is 1−, then the positron decay most likely occurs to the ground state of ^{168}Yb, favoring $Q=2.2$ MeV. The energy difference between ^{168}Lu and ^{168}Yb is predicted to be 4.6 MeV by Cameron and 3.8 MeV by Levy. The 3.2 MeV experimental value would be more consistent with these values than the 2.2 MeV value. The maximum γ-ray energy of 2.1 MeV requires the energy difference to be at least 2.1 MeV, which is in good agreement with the 2.2 MeV value from above. If the positron decay is to the 986-keV 2+2 level in ^{168}Yb, then a spin of 2+ for ^{168}Lu would imply an allowed transition. The absence of a positron in the 2-h activity and the existence of only one predominant γ ray of 87 keV might be more consistent with a spin of 1− for the 2-h state of ^{168}Lu with decay to the ground and first rotational states of ^{168}Yb via electron capture only; $\Delta I=1$ and parity changes.

A proposed decay scheme for the neutron-deficient nuclides of A 168 is shown in Fig. 1. The data for ^{168}Hf are from Ref. 3; those for ^{168}Lu are developed from Refs. 2–4. The higher-energy levels in ^{168}Yb are based on γ-ray pair energy differences of about 85 or 90 keV in the decay of ^{168}Lu and levels observed in Ref. 4. The numbers following the transition energies are approximate relative transition intensities. A logical 717-keV transition is shown dashed in Fig. 1 between two possible spin-1 levels; this could be the 0.71-MeV transition reported by Merz and Caretto.[3] The decay and transition intensities shown in Fig. 1 are the best that can be done with existing information, are only very approximate in some cases, and should be considered subject to modification.

The interpretations, which can be made of the levels in ^{168}Yb, apparently populated in the decay of the 7-min ^{168}Lu activity are discussed below. The 986-keV level was originally assumed[1] to be the 2+2 γ-vibrational level. This has been substantiated in Ref. 4. However, the experimental branching ratio for decay to the ground-state band, $(2+2\rightarrow 2+0)/(2+2\rightarrow 0+0)=0.8$, is somewhat low. The possibility exists that there is at least one other γ ray of energy close to 1.0 MeV, e.g., one from the 2± level at 2.0 MeV to the 1.0, MeV 2+ level.

The 1233-keV level is assumed to be the first rotational level (2+0) of the β vibrational band based at about 1154 keV, in agreement with Ref. 4, where the 1154 (0+0) and the 1391 (4+0) levels were observed. The experimental branching ratio $(2+0\rightarrow 2+0/2+0\rightarrow 0+0)=1.5$ is in good agreement with theory.

A spin-1 level is tentatively assigned at 1410 keV based on the observation of γ rays of 1410 and 1325 keV with a resulting decay branching ratio of

$$(x\rightarrow 2+0)/(x\rightarrow 0+0)=0.2,$$

which seems consistent with a spin of 1. A 3-octupole vibrational level is assigned at 1475 keV by Burke and Elbek.[4] It is postulated that this 1410-keV level is the 1− component of an octupole vibrational band composed of the 1410- and 1475-keV levels. The possible choice of 1− for the spin of ^{168}Lu would explain why only the 986-, 1233-, and 1410-keV levels are populated in the decay.

A 1550-keV level was observed in Ref. 4. The 1465-keV γ ray observed in the ^{168}Lu decay could be a transition from this level to the 2+0 ground-state level. This assignment is only tentative. A firmer assignment of a level at about 2000 keV can be made based on the observation of γ rays of 2000 and 1915 keV and a level at about 2000 keV in Ref. 4. The experimental decay branching ratio of approximately unity suggests a spin of 2 for this level.

A single γ ray at ∼2130 keV can be matched to the ∼2125-keV level of Ref. 4 with a suggested spin of 1. There is the possibility that the peak at 2130 keV comprises rather two γ rays of 2195 and 2110 keV which would allow a match to a ∼2195-keV level which can be inferred from the data of Ref. 4, but is not suggested by the authors. A spin assignment of 2 would be indicated, for the possible 2195-keV level.

[4] D. G. Burke and B. Elbek, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **36**, 6 (1967).