Excited states in the doubly odd ^{168}Lu nucleus fed by electron-capture decay of ^{168}Hf ($T_{1/2}$=25.95 min)

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The low-spin levels of the odd-odd nucleus ^{168}Lu from ^{168}Hf ($T_{1/2}$=25.95 min) electron-capture decay were investigated by direct γ and $\gamma-\gamma$ coincidence measurements. The sources of ^{168}Hf were produced with the ^{156}Gd(^{16}O,4n) reaction and radiochemically separated using chromatographic methods. A level scheme of 39 new levels in the ^{168}Lu nucleus was proposed, accounting for 107 of 119 observed γ transitions assigned to ^{168}Hf electron-capture decay. Transition multipolarities, level-spins, and parities were deduced or proposed. A tentative decay scheme was proposed. Level structure was discussed in the framework of the particle-rotor and Nilsson models. [S0556-2813(97)06005-6]

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I. INTRODUCTION

Doubly odd nuclei are less attractive from the experimental point of view: level densities are very high and γ spectra may be composed of many superimposed transitions, so the analysis is difficult and requires high-resolution spectroscopy methods. Furthermore, theoretical calculations are rare. But with oversimplified models, matrix elements of interactions between involved particles grow rapidly to saturation of computer capabilities. Nevertheless such nuclei would be of significant interest for the knowledge of the proton-neutron interaction in nuclear matter.

In the framework of our research program for the production and chemical separation of the element $Z=104$ we carried out a test experiment of the RACHEL (Rapid Aqueous Chemistry Apparatus for Heavy Elements) facility with the ^{156}Gd(^{16}O,4n)^{168}Hf reaction, producing the chemically homolog element hafnium ($Z=72$).

The ^{168}Hf ($\epsilon+\beta^+$) decay was poorly known. No level scheme was clearly established for the nucleus ^{168}Lu, as reported in Nuclear Data Sheets (NDS) (Ref. [1], and references therein). Only conversion electrons of twenty transitions [2] and two γ rays of 157- and 183-keV energy [3] were assigned to ^{168}Lu, but not placed in level scheme. Only two states were reported, two isomers: a $J^\pi=(6^-)$, 5.5-min ground state (g.s.) and a $J^\pi=3^+$, 6.7-min level at 220 $\pm$130 keV, known from their ($\epsilon+\beta^+$) decay [4]. Neighboring doubly odd nuclei ^{168}Lu [5,6] and ^{170}Lu [7,8] are better known and show rapid variations of intrinsic structures. In the former three isomers were clearly identified: a $J^\pi=6^-$ ($T_{1/2}$=2.65 min) g.s.; a $J^\pi=3^-$ ($T_{1/2}$=1.47 min) 34.37-keV level, and a $J^\pi=0^-$ ($T_{1/2}$=2.12 min) 42.9-keV level. In the latter two isomers were detected: a $J^\pi=0^+$ ($T_{1/2}$=2.01 d) g.s. and a $J^\pi=(4)^-$ ($T_{1/2}$=0.67 sec) 92.9-keV level. Rotational structures were also clearly assigned. In the present paper we report a new study of the ($\epsilon+\beta^+$) decay of ^{168}Hf carried out at the IPN (Institut de Physique Nucléaire) Tandem facility in Orsay.

II. EXPERIMENTAL PROCEDURES

Enriched ^{156}Gd targets (>99% purity) were produced at the PARIS mass separator of the CSNSM (Centre de Spectroscopie Nucléaire et Spectroscopie de Masse) in Orsay: 500-μg cm^{-2} gadolinium were backed on 8-mm thick aluminum foils and covered by a 20-μg cm^{-2} carbon layer to prevent oxydation.

The beam of $^{16}O^{7+}$ ions from the 15-MV tandem facility in Orsay was set at 100-MeV energy to obtain, after window and target slowing down, the 75-MeV energy of the cross-section maximum for the (^{16}O,4n) compound nucleus reaction. The optimun energy was estimated by calculation with the ALICE code [9] and monitored in a prior experiment with variable beam energy. Weak contributions from near channels: $3n+^{169}$Hf ($T_{1/2}$=3.24 min) and $5n+^{167}$Hf ($T_{1/2}$=2.05 min) were also present and estimated to be lower by more than one order of magnitude, from comparison of leading order decay transitions. Reaction products were collected either directly on a 10-μm thick aluminium foil, 1 mm behind the target, for off-line separation, or with a helium jet facility, charged with KCl aerosols, for on-line separation.

The chemical separation was carried out on-line with the RACHEL facility, described elsewhere [10]. Basically Hf, as anionic complex $[HfF_6]^{2-}$, is column-fixed by ion-exchange chromatographic methods, while trivalent cationic lanthanide ions are removed by continuous elution processes.

90-min irradiation steps were performed, at about 600-nA beam energy. Short-lived isotope (^{167}Hf and ^{169}Hf) activities were rapidly close to saturation and mainly long-lived ^{168}Hf grew.

γ-ray and x-ray direct and coincidence measurements were carried out with three HPGe (High Purity Germanium) detectors: a planar detector, 20-cm^2 area, 0.5-keV full width half maximum (FWHM) resolution at 122 keV, at the top of the anionic column in the coincidence setup; a 40% relative efficiency, 1.75-keV resolution at 1.33 MeV, at the bottom, 180° to the first; a 20% efficiency, 1.89 keV resolution, at 90° in the horizontal plane. All detectors were shielded with

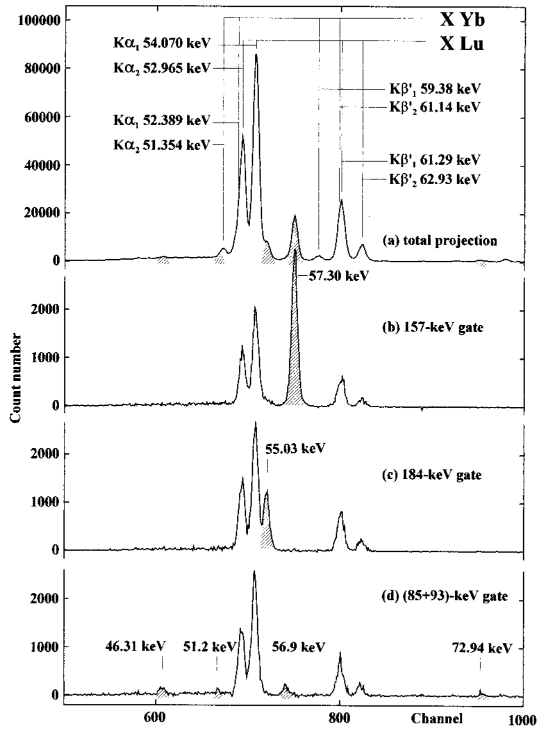

FIG. 1. Comparison of spectra of the planar detector for the same energy interval in total projection and selected coincidence gates: (a) total projection, (b) 157-keV gate, (c) 184-keV gate, (d) (85+93)-keV gate. Coincidence peaks, except for x rays, are cross-hatched.

a 5-cm thick lead box, inside covered by a 1.5-mm thick copper foil.

Direct γ- and x-ray spectra were stored on 8- or 4-K channel multichannel analyzers (MCA) driven by PC software. $\gamma-\gamma$ coincidence events, within 150-ns gate time, were recorded on magnetic tape, for further off-line analysis. A total $\approx 3.4\times 10^6$ events were stored. Coincidences matrices were sorted for any detector pair. Gates on any γ of sufficient intensity were settled. Figure 1 shows some selected portions of coincidence spectra. Direct spectra were analyzed with the computer code GAMANAL [11]. Nuclear calculations were carried out with the program package of the ENSDF (Evaluated Nuclear Structure Data Files) program library, obtained from NNDC (National Nuclear Data Center, Brookhaven).

III. EXPERIMENTAL RESULTS

A. Transitions and assignments to level scheme

Energies and intensities were measured with proper calibrations of the detectors, using standard reference sources. 107 γ out of 119 (Table I) may be assigned to 39 levels in the nucleus ^{168}Lu (Table II). The assignments to level scheme were based on coincidence relations. A few weak transitions were assigned according to energy difference relations, similar to Ritz's combination principle in optical spectroscopy.

Tentative assignments for spins and parities were made according to the following (weak) arguments.

(i) Calculated conversion-electron subshell ratios from measured conversion-electron intensities [2] were compared with theoretical values [12].

(ii) Measured asymmetries, from $W(180°)/W(90°)$ angular distribution ratio, were compared with theoretical values for given level spin sequences.

(iii) The β-decay selection rules from a 0^+ ground state of even-even parent demand that only low spin states in the daughter be appreciably populated, so all observed transitions were supposed of dipole and/or quadrupole character, except where noted.

(iv) Multipole mixing in a transition was not indicated if unknown.

(v) From intensity considerations concerning our experimental setup, a lower or detection limit of 0.7 experimental units, relative to 183-keV γ-ray intensity taken as 100, was established; transitions with conversion coefficients greater than $100/0.7\approx 150$ were unobservable in γ channel; so from theoretical conversion coefficient tables [12]: (a) $E1$ transitions were always observable, at least for $E_\gamma > 5$ keV, the detector energy threshold; (b) $M1$ transitions were unobservable for $E_\gamma < 20$ keV; (c) $E2$ transitions were unobservable for $E_\gamma < 45$ keV.

(vi) Many low-energy transitions observed as γ emissions were not detected in electron channel [2]: all transitions with intensities greater than 10 and not observed as conversion-electron lines were supposed of $E1$ character.

(vii) No $E0$ multipolarity was considered.

The assignments are equally reported in Tables I and II.

B. Isomers and isomeric transition (IT)

Two isomers were known in ^{168}Lu Charvet *et al.* [4] measured $\gamma-\beta^+$ coincidences and reported two end-point energies for the β^+ spectrum; therefore they proposed two isomeric levels, a ($T_{1/2}=5.5$ min) g.s. and a ($T_{1/2}=6.7$ min) state at 220 ± 130 keV. The g.s. was assigned $J^\pi=(6^-)$ from strong feeding of the 2110.6-keV, $J^\pi=(5^-,6^-,7^-)$, level in ^{168}Yb. The spin of the isomeric state with a 6.7-min half-life was measured [14] to be $J=3$ by atomic beam techniques; the parity was deduced due to strong feeding to positive parity states in the daughter. This $J^\pi=3^+$ level is the only isomer observed in our experiment from the ϵ decay of the $J^\pi=0^+$ parent. A weak 202.8-keV γ, with measured high conversion rate [2], might be proposed as a candidate for the isomeric transition, according to the following remarks. Parent and daughter nuclei (25.95-min ^{168}Hf, 6.7-min ^{168}Lu 3^+ isomer) were not in equilibrium condition in our experiment. As previously mentioned the column with fixed hafnium anionic complex was continuously eluted to keep away daughter lanthanide cations. Low contamination were possible due to finite transport time and weak retention of Lu^{3+} cations at the resin grains, so that radiations below the $J^\pi=3^+$ isomer were intensity lowered by one order of magnitude with respect to equilibrium conditions, as, e.g., was the case in Harmatz and Handley's experiment [2]. This attenuation factor was found 5.4 ± 1.3 and could be calculated from comparison of intensities of the 87.7-keV γ, belonging to the $2^+\rightarrow 0^+$ $E2$ transition in ^{168}Yb, present as Lu decay contamination in Hf decay spectra, and with known absolute γ intensity, relative to 100 decays of the parent [1]. The total

TABLE I. Energy, intensity, and assignment of γ transitions from ^{168}Hf (25.95 min) ε decay. Standard uncertainties in the last significant digits are given in parentheses. Relative photon intensities are normalized to the intensity of the 183.93-keV γ taken as 100. For absolute intensity per 100 ($EC+\beta^{+}$) ^{168}Hf decays, multiply by 0.075 (9). A blank cell in the column of energy of initial level denotes a γ transition not placed in the ^{168}Lu level scheme. Multipolarities are deduced according to the arguments of the text; values in parentheses are weak assignments.

E_γ (keV)	I_γ (relative)	E (initial level) (keV)	Multipolarity
14.40(5)	1.00(10)	591.83	
17.53(9)[a]	1.70(20)	55.05	
24.25(3)	13.1(15)	238.97	$(M1+0.7\%E2)$
27.82(7)	1.20(20)	36.10	
29.80(7)	0.80(10)	38.04	
35.9(5)[b]	<0.7	36.10	
38.04(5)	1.30(20)	38.04	
43.07(12)[a]	2.30(20)	100.90	
44.21(12)	4.3(4)		
46.31(6)	2.4(3)	147.28	
49.0(5)[b]	<0.7	57.32	
51.2(5)[b]	5.8(10)[c]	152.07	
55.03(10)	60.5(4)	55.05	$M1+2.5\%E2$
56.9(5)[b]	4.9(10)	157.80	$(M1)$
57.30(10)	137.0(10)	57.32	$(E1)$
61.92(10)	10.6(10)[c]	117.249	$(E1+8\%M2)$
64.81(4)	3.0(3)	225.34	
68.23(15)	1.30(10)	228.52	
70.96(9)	2.7(3)[d]	228.52	
72.94(5)	9.9(10)[c]	173.99	
74.94(8)	15.1(15)[c]	192.38	
79.05(7)	2.6(3)	117.249	
85.47(3)	40.6(24)	100.90	$(E1)$
86.96(6)	12.8(8)	238.97	$(E1)$
89.57(8)	1.00(10)	190.64	
91.58(6)	1.80(20)	192.38	
92.68(3)	47.5(30)	100.90	$(E1)$
97.46(3)	70(4)	214.71	$(E1+17\%M2)$
99.65(6)	1.60(20)		
105.76(8)	1.50(20)	160.58	
106.81(6)	1.80(20)		
108.10(3)	5.2(3)[c]	225.34	
111.32(6)	2.7(3)	147.28	
113.68(6)	3.3(3)[c]	214.71	$(E1)$
115.84(5)	2.9(3)	152.07	
117.30(3)	87(4)	117.249	$(E1+24\%M2)$
119.92(8)	1.30(10)	190.64	
122.56(3)	10.2(6)	160.58	
138.38(11)	3.4(10)	238.97	$(E1)$
139.07(10)	2.7(10)	147.28	
401.21(9)	7.5(6)	591.83	
417.62(9)	22.1(16)	591.83	
424.26(9)	3.7(4)	591.83	
434.14(6)	35.6(25)	591.83	$(E1)$
439.94(8)	9.0(8)	591.83	$(E1)$
474.62(6)	5.4(4)	591.83	
490.87(6)	29.2(20)	591.83	$(E1)$
493.02(9)	5.3(4)		
534.45(6)	19.4(13)	591.83	$(E1)$
536.76(9)	3.3(3)	591.83	$(M1)$
576.42(6)	8.4(7)	591.83	$(M1)$
583.59(9)	2.0(2)	591.83	$(M1)$
640.10(9)	1.20(10)		
706.36(9)	0.80(10)[c]		
712.08(9)	1.30(10)		
724.69(6)	2.7(3)	841.94	
737.20(9)	1.00(10)		
142.44(3)	14.9(9)	157.80	$(E1)$
143.91(3)	18.7(11)	152.07	$(E1)$
149.64(3)	13.9(8)	157.80	$(E1)$
152.31(5)	6.9(5)	167.66	
154.72(8)	2.30(20)	190.64	
157.41(3)	71(4)	214.71	$(E1)$
159.4(5)[b]	3.0(10)	167.66	
159.66(3)	41(3)	214.71	$(M1+28\%E2)$
160.59(6)	5.6(5)	160.58	
171.13(15)	3.3(3)	228.52	
175.60(16)	3.2(3)	577.45	
181.65(3)	66(4)	238.97	$(E1)$
183.93(3)	100.0(10)	238.97	$(M1)$
189.46(15)	4.9(5)	591.83	
192.33(5)	14.7(12)	228.52	
199.33(5)	9.5(8)	214.71	$(M1)$
202.81(12)	0.75(9)		
206.46(6)	31.6(10)	214.71	$(M1)$
208.14(5)	6.0(6)	223.51	
210.07(9)	4.2(4)	591.83	
213.01(9)	2.00(20)	228.52	
214.56(8)	3.1(3)	214.71	
217.13(6)	11.1(7)	225.34	
220.23(10)[b]	0.70(10)	228.52	
223.51(5)	9.0(10)[c]	223.51	
225.23(6)	8.2(6)	225.34	
230.75(3)	11.0(7)	382.82	
234.41(8)	2.40(20)	392.22	
238.26(15)	1.40(10)[c]		
240.15(6)	4.3(4)	392.22	
277.29(6)	2.9(3)	277.29[a]	
324.11(5)	8.7(7)	381.51	
345.08(6)	11.2(8)	402.33	
349.02(9)	2.00(20)	516.69	
352.87(9)	6.4(5)	591.83	$(M1)$
363.36(6)	15.2(10)	591.83	
368.33(9)	5.7(5)	591.83	
372.78(15)	0.90(10)[c]		
377.50(14)	9.2(7)	591.83	$(M1)$
391.37(9)[a]	2.6(3)	969.9	
740.49(9)	1.00(10)	1017.78[a]	
747.15(9)	1.10(10)	1128.68	
837.35(9)	1.40(10)		
866.14(15)	2.20(20)	1105.12	
872.11(15)	1.30(10)	973.01	
901.7(3)	0.90(10)[c]		
912.6(3)	1.60(20)	969.9	
937.52(9)	2.7(3)	1038.42	
988.0(3)	2.6(3)	1105.12	
1004.0(3)	1.70(20)	1105.12	
1047.9(3)	1.80(20)	1105.12	
1071.6(3)	2.9(3)[c]	1128.68	
1091.4(3)	6.0(5)[c]	1146.68	
1096.0(6)	2.50(20)		
1119.2(6)	1.30(10)[c]		
1193.1(9)	1.00(10)[c]		
1311.3(9)	0.70(10)		

[a]Placement in level scheme is uncertain.
[b]γ transition only observed in γ-γ coincidences.
[c]Transition intensity corrected for x-ray or ^{168}Lu decay contribution.
[d]Multiple γ with unplaced component, total intensity.

TABLE II. Adopted levels in ^{168}Lu. Level energies were calculated from least squares fit to γ energies. Uncertainties are given in parentheses. Spin and parity assignments were given according to arguments of the text unless otherwise stated. Spin values in parentheses are weak assignments.

E (keV)	J^π	$T_{1/2}$ (min)	E (keV)	J^π
−202.81(13)[a]	(6^-)[b]	5.5(1)[c]	223.51(4)	(1-3)
0.0	3^+[d]	6.7(4)[e]	225.34(3)	(1)
8.20(3)	$(1^+,2^+)$		238.97(3)	1^+
15.38(3)	$(0^+$-$2^+)$		277.29(6)[a]	
36.10(4)	(1-3)		381.51(6)	(1,2)
38.04(3)	(1-3)		382.82(4)	(0,1)
55.05(3)	2^+		392.22(6)	(0,1)
57.32(3)	(2^-)		402.33(6)	(0-2)
70.72(10)[a]			516.69(11)	(0,1)
100.90(3)	$(0^-$-$2^-)$		577.45(5)	(0-2)
117.249(23)	(2^-)		591.83(3)	(1^+)
147.28(4)	(0-2)		841.94(7)	(0,1)
152.07(4)	$(0^-$-$2^-)$		969.9(3)	(0,1)
157.80(4)	$(0^-$-$2^-)$		973.01(16)	(0,1)
160.58(3)	(1-3)		1017.78(11)[a]	
167.68(6)	(0-2)		1038.42(10)	(0,1)
173.99(5)	(0-2)		1105.12(12)	(0,1)
190.64(6)	(0-2)		1128.68(10)	(0,1)
192.38(6)	(0,1)		1146.68(10)	(0,1)
214.71(3)	$(1^+,2^+)$			

[a]Placement is uncertain.
[b]From Ref. [4].
[c]From Refs. [4,13].
[d]From Ref. [14].
[e]From Refs. [4,13–17].

intensity of the 202.8-keV transition, if really IT decay, could be estimated, for an $E3$ character ($\alpha_{\text{total}}=1.85$ [12]), as 0.86 ± 0.21 per 100 decays. This is much lower than, but compatible with IT<5%, proposed by Charvet *et al.* [4], or <4.5% by Arlt *et al.* [18]. This transition is very weak in the γ channel: it was only observed in the total sum spectrum of all irradiations, so it was considered doubtful and therefore in our paper level energies will be referred to the $J^\pi=3^+$ isomer as ''ground state.''

C. $(\epsilon+\beta^+)$ decay

A tentative decay scheme was proposed as shown in Fig. 2. From level scheme and multipolarity assignments total intensity balances were calculated at each level. Some additional assumptions were needed. From γ intensity balances three levels might share most of the decay intensity, at 591, 239, and 214 keV. The 25-keV transition connecting the 239- and 214-keV levels was most probably assigned a $M1+E2$ character from measured L_1/L_2 and L_1/L_3 electron-conversion intensity ratios [2]. The $M1+E2$ conversion coefficient is greater than 40 [12]: that is, more than sufficient to account for all intensity feeding the 214-keV level. Here the intensity balance requires that the strong 97-keV transition catches most of the missing intensity. The conversion coefficient for this transition must be $\alpha_T\approx7$, which can be achieved only by a mixed $E1+M2$ transition. Equally, the strong 117-keV transition, in direct coincidence with the 97-keV γ, feeding the g.s. must be enhanced by a conversion process of the same amount. A conversion coefficient of $\alpha_T\approx4.8$ is required for this mixed $E1+M2$ transition.

From decay intensities, significative populations were only found for the 591- and 239-keV levels. Weak feedings were only considered for higher energy levels with no incoming γ. For all other levels total intensity balances are consistent with zero at the three-standard-deviation confidence level. Most of the decay intensity can be attributed to the 239-keV level, with ≈75% of the decay, and to the 591-keV level, with ≈15%; the remaining 10% is shared among several weak ϵ branches and/or a few unknown transitions. For low-energy levels weak imbalances were found, which could be easily explained by badly known conversion processes and/or weak unobserved transitions; e.g., at the 57-keV level, a weak $M2$ mixing in the 57-keV $E1$ transition to the g.s. would be sufficient to balance the excess of incoming intensity. No attempt was made to estimate such processes, except for the strong coincidence cascade of the 24-, 97-, and 117-keV transitions.

Tentative calculations of logft values were performed. Different hypotheses may be put forward. No direct measurement of the experimental Q_{β^+} value of the ^{168}Hf ground state relative to ^{168}Lu was ever performed. The Atomic Mass Tables (AMT) [19] report a value $Q_{\beta^-}=-1800\pm130$ keV from systematics studies. Merz and Caretto [16] measured. β^+ spectra of a ^{168}Hf source and found two β^+ end-point energies. The former (1.2±0.1 MeV) was assigned to the ^{168}Lu daughter, and was observed also by Charvet *et al.* [4] who measured 1.230±80 keV, but assigned it to the 5.5-min (6^-) isomer; the latter (1.7±0.1 MeV) was assigned to ^{168}Hf (25.95 min). End-point energies between 1.47 [4] and 2.70 MeV [20] were measured for the 6.7-min isomers, so the attribution of Merz and Caretto may be questionable. With their experimental value assigned to the transition to the most populated state at 239 keV above the 3^+ isomeric state, a $Q_{\beta^+}=2960\pm100$ keV relative to the 3^+ state can be estimated, which is far greater than systematics trends.

logft calculations were performed with this value and also with systematic AMT values referred to 3^+ state, and (6^-) state. In Fig. 2 we report this latter calculation with $Q_{\beta^+}=1600\pm150$ keV, where the energy difference between the isomers was estimated ≈200 keV. Significative β^+ intensities were possible only with the former value: the transition to the 239-keV level account for 8.8% β^+ of the total decay. This is much more than the 1–3 % estimated by the authors [16]. It was evident from all calculations that lnft values for decay to the 239- and 591-keV levels range from 4.7 to 5.9, compatible with allowed ($\Delta I=1$, $\Delta\pi=+$) transitions [21,22]. All other transition logft's range from 7 to 8, compatible with first-forbidden ($\Delta I=0,1$, $\Delta\pi=\pm$) transitions.

IV. DISCUSSION

Neighboring nuclei are well deformed and exhibit well-defined rotational bands. For the ^{166}Yb core nucleus [5] a quadrupole deformation $\beta_2\approx0.28$ can be calculated from the semiempirical Grodzins's relation [23] and the experimental

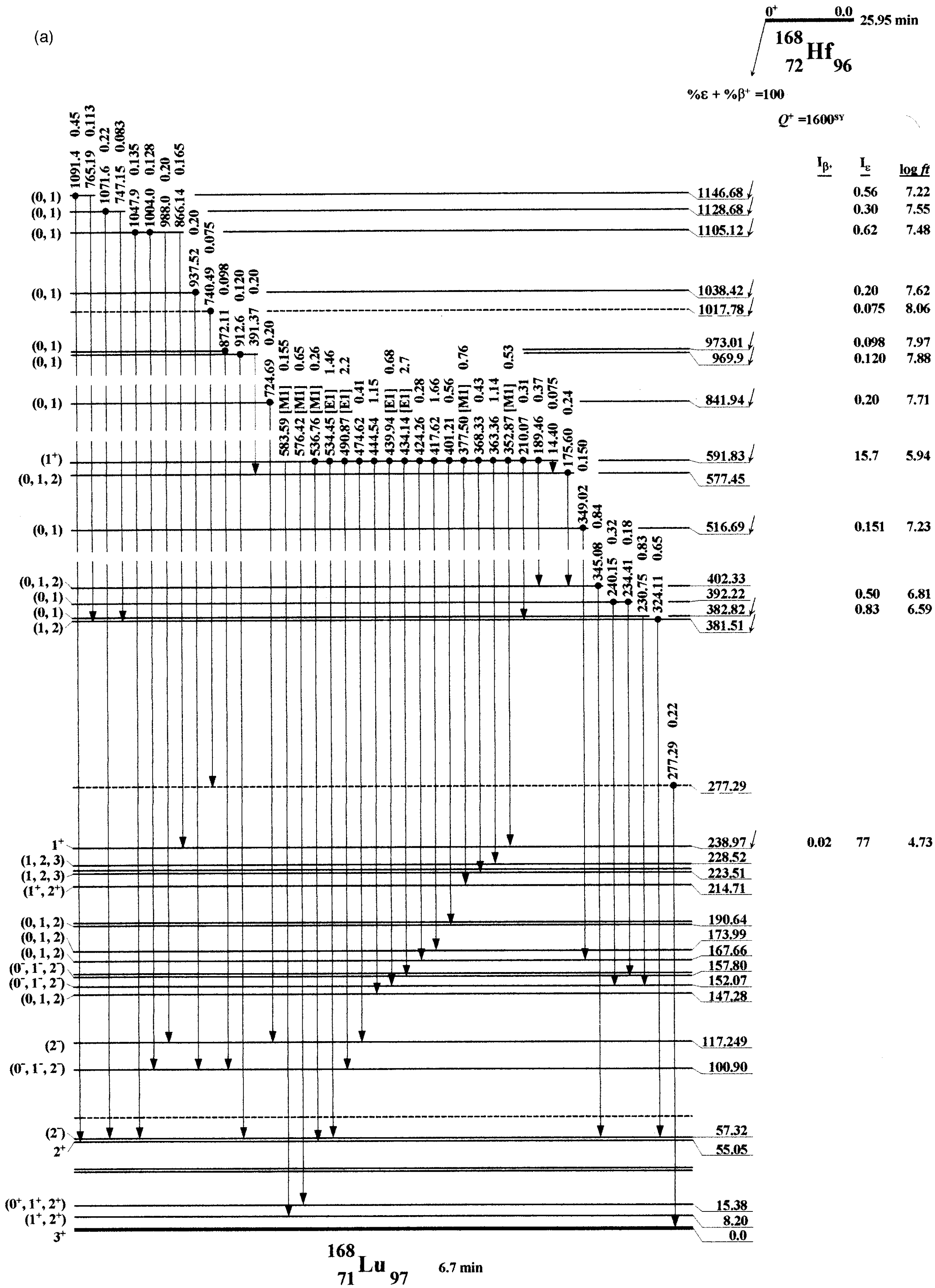

FIG. 2. Decay scheme of ^{168}Hf ($T_{1/2}$=25.95 min): (a) high-energy levels, (b) medium-energy levels, and (c) low-energy levels. Dots denote observed coincidences. Open arrowheads denote transitions not observed in γ channel, but deduced from level scheme, coincidence relations and intensity balance considerations.

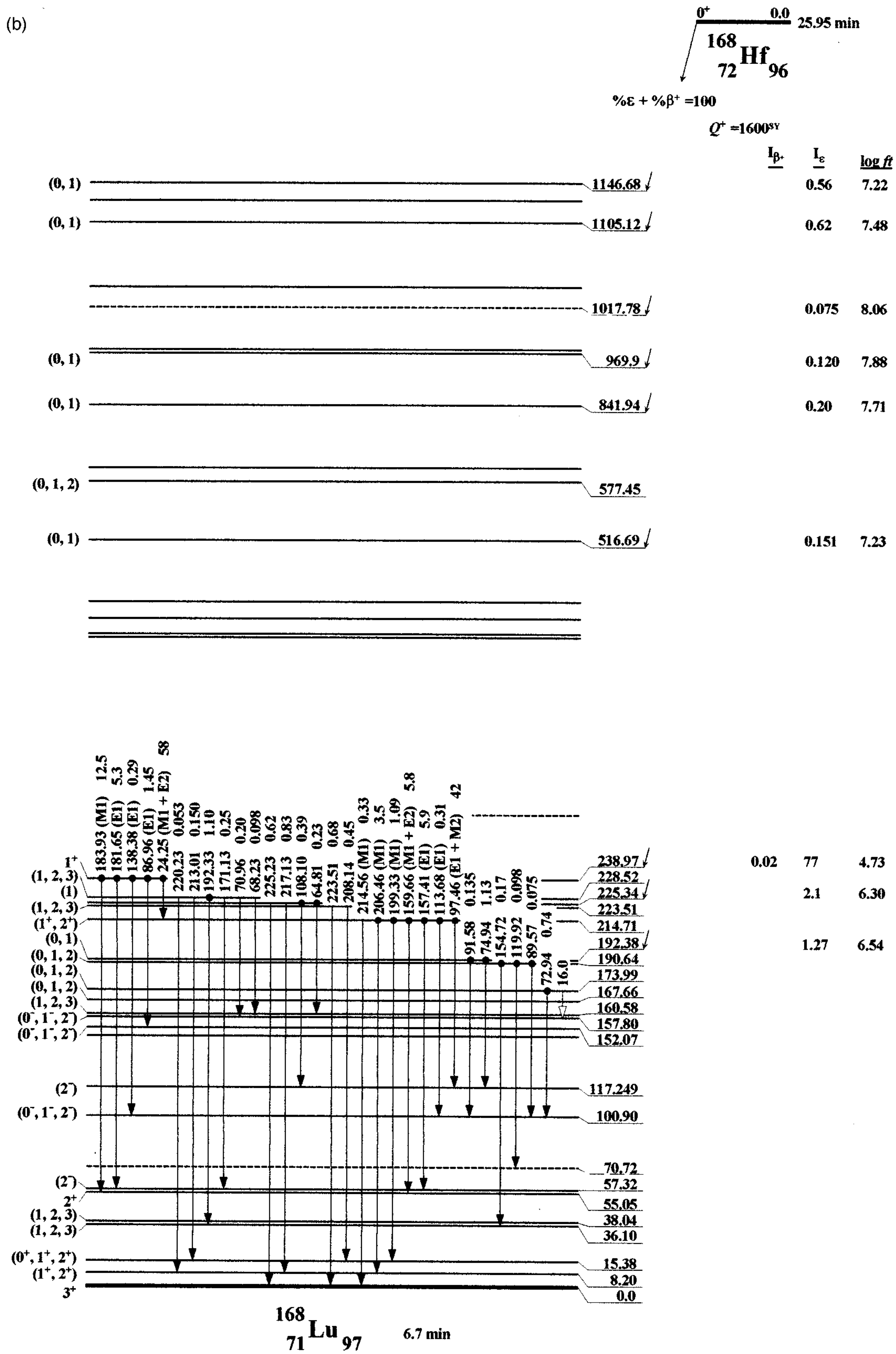

FIG. 2. (*Continued.*)

values of the energy differences in the g.s. band. Equally for the parent ^{168}Hf [1] we have $\beta_2 \approx 0.25$. Nilsson states are adequate to describe the structure of such nuclei.

Proton-neutron configurations pertinent to the odd-odd ^{168}Lu nucleus, can be deduced from the odd-mass neighboring nuclei ^{167,169}Lu for single-proton and ^{167}Yb, ^{169}Hf for single-neutron configurations (Fig. 3). Unfortunately the level sequence of the 71th proton is badly known in ^{167}Lu.

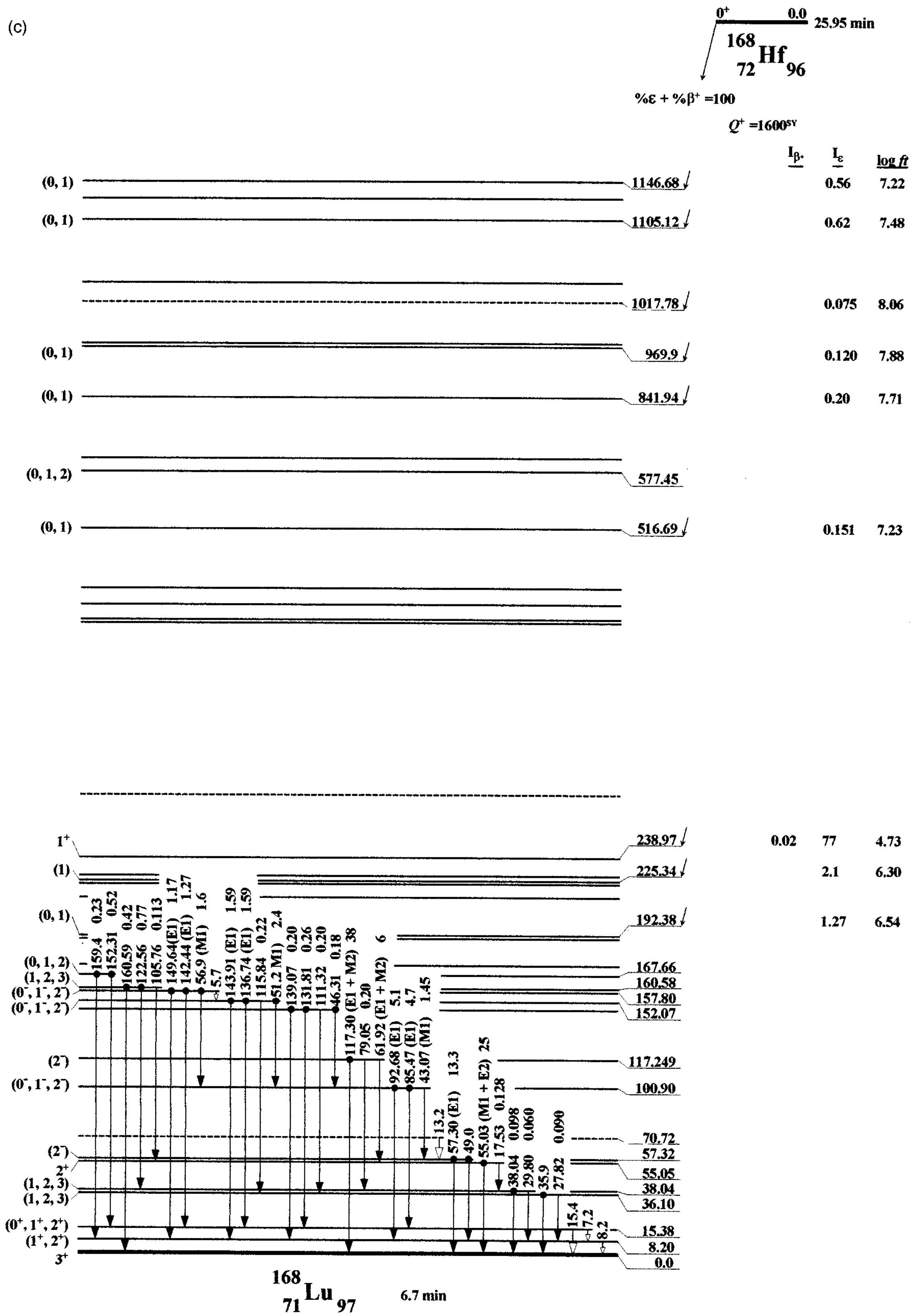

FIG. 2. (*Continued*).

The 71 proton level as well as the 97th neutron level systematics are reported in Fig. 4, from measured level energies as compiled in NDS ([24], and references therein).

Allowed unhindered β transitions are well-known in this region and involve spin-orbit partners $\nu 5/2^-[523] \leftrightarrow \pi 7/2^-[523]$, which lie close to Fermi level. This transition exists in many nuclei all around, with log$ft \approx 4.8$ (see [25], p. 307); e.g., in ϵ decay of ^{167}Yb to an excited state

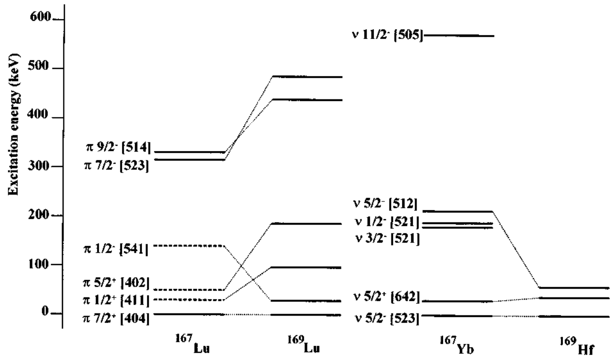

FIG. 3. Experimental assigned Nilsson states in odd-mass nuclei neighboring of ^{168}Lu. Broken lines denote uncertain placements.

(293 keV) of ^{167}Tm. So, the most probable configuration of the 1^+ state in ^{168}Lu is $\pi 7/2^-[523]-\nu 5/2^-[523]$, from the breaking of a proton pair in the filled $\pi 7/2^-[523]$ orbital of the parent. Such a configuration was proposed in the close ^{166}Lu by de Boer *et al.* [6] for the 136.0-keV level, populated at $\approx 75\%$ in $\epsilon+\beta^+$ decay of ^{166}Hf with log*ft* ≈ 4.6. Similar structures were also proposed by Charvet *et al.* [4] to account for allowed transitions of the ^{168}Lu isomers. The (6^-) (5.5 min) isomer was proposed; with a configuration $\pi 7/2^+[404]+\nu 5/2^-[523]$ and the most populated state in the daughter ^{168}Yb, with log*ft* ≈ 4.8 were assigned the configuration $7^-(\pi 7/2^+[404]+\pi 7/2^-[523])$. Equally the 3^+ (6.7 min) was proposed $\pi 1/2^-[541]+\nu 5/2^-[523]$ feeding a

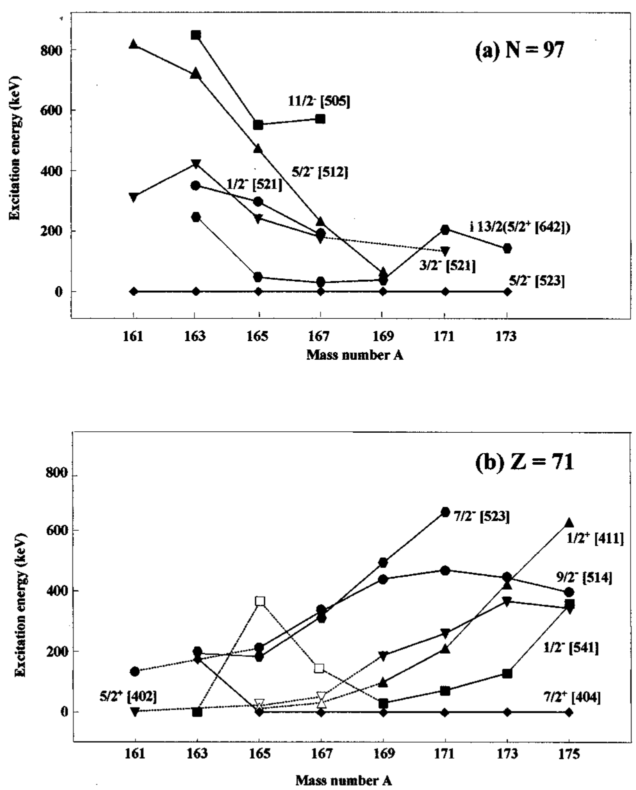

FIG. 4. Experimental systematics of odd-mass nuclei: (a) $N=97$, (b) $Z=71$. Open symbols denote uncertain placements; full and broken lines connect like levels.

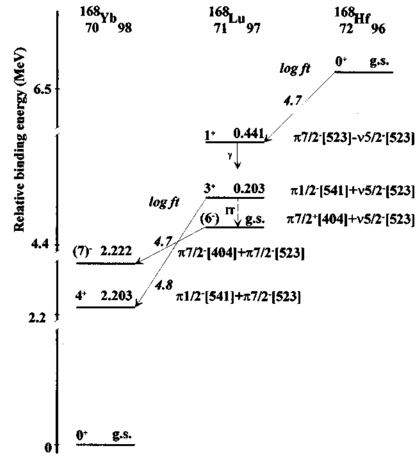

FIG. 5. Allowed unhindered β transitions in $A=168$ isomers.

$4^+(\pi 1/2^-[541]+\pi 7/2^-[523])$ state with log*ft*≈ 4.8 (Fig. 5).

The calculation of log*ft* with the systematic Q value from the mass tables, referred to (6^-) g.s. $(Q_{\beta+}=1600 \pm 150$ keV$)$, gives 4.73 in good agreement with the preceding interpretation. This may be a weak reason to prefer this Q value.

These states considered in ^{168}Lu have configurations where the neutron orbital is the same: the difference only comes from proton orbitals. The comparison with the level scheme of the single-proton core nucleus ^{167}Lu shows a qualitative agreement (Fig. 6).

A simple interpretation of the energy levels in ^{168}Lu may be made in the framework of the particle-rotor model (see Ref. [25], p. 199). The even-even core ^{166}Yb plus one proton and one neutron may be described by the approximated Hamiltonian

$$H=H_{\rm rot}+H_p+H_n+H_{\rm int},$$

where the rotational Hamiltonian [26] is

$$H_{\rm rot}=\frac{\hbar^2}{2\mathcal{J}}(\mathbf{I}^2-2I_3^2+2j_{p3}j_{n3}+\mathbf{j}_p^2+\mathbf{j}_n^2),$$

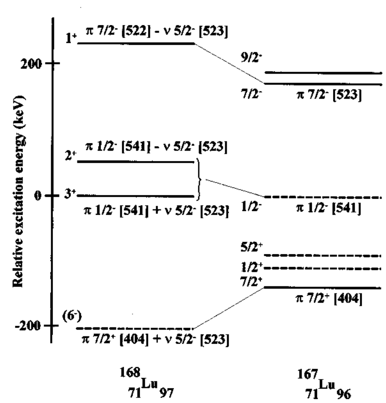

FIG. 6. Comparison of selected parts of level schemes in ^{168}Lu and ^{167}Lu with proposedlike structures.

TABLE III. Band energies from quasiparticle excitations in odd-mass nuclei adjacent to ^{168}Lu; rotational parameters in adjacent odd-mass and even-even nuclei. Uncertainties given in parentheses are experimental spreads in two neighboring odd-mass nuclei.

	Odd proton states Average of data[a] for ^{167}Lu and ^{169}Lu				Odd neutron states Average of data[a] for ^{167}Yb and ^{169}Hf		
	Proton orbital	E (K) (keV)	A (keV)		Neutron orbital	E (K) (keV)	A (keV)
A	$7/2^+[404]$	0.0	15.2(15)	Z	$5/2^-[523]$	0.0	10.9(1)
B	$1/2^+[411]$	97(48)[b]	13.3(5)[c]	Y	$5/2^+[642]$	34(4)	6.89(6)[e]
C	$1/2^-[541]$	107(49)[b]	10.0(3)	X	$5/2^-[512]$	136(77)	14.1(5)
D	$5/2^+[402]$	186(93)[b]	16.1(14)	W	$3/2^-[521]$	180(100)[f]	11.9(13)[f]
E	$9/2^-[514]$	385(54)	9.0(3)	V	$1/2^-[521]$	188(100)[f]	13.6(10)[f]
F	$7/2^-[523]$	404(89)	14.1(1)[d]	T	$11/2^-[505]$	572(100)[f]	12.7(7)[f]

Even-even nuclei[g]
$A(^{168}\text{Yb})=14.7$ keV
$A(^{168}\text{Hf})=20.4$ keV

[a]From Ref. [24].
[b]Uncertainty account for uncertain placement of the level in ^{167}Lu.
[c]From ^{169}Lu only; uncertainty quoted as $\Delta A=|A(^{169}\text{Lu})-A(^{171}\text{Lu})|$.
[d]Arithmetic mean from ^{163}Lu and ^{171}Lu.
[e]Strongly Coriolis perturbed $i_{13/2}(5/2[642])$ configuration.
[f]From ^{167}Yb only; estimated uncertainties $\Delta E=100$ keV, $\Delta A=|A(^{167}\text{Yb})-A(^{165}\text{Er})|$.
[g]From Ref. [1].

$\mathcal{J}$ is the moment of inertia of the odd-odd nucleus, **I** is the total spin. H_p and H_n are the single-particle Nilsson-type Hamiltonians for one particle in a deformed axial-symmetric well with intrinsic spin **j**, and H_{int} is a proton-neutron residual interaction of Gallagher-Moszkowski (GM) type [27].

In the basis of the unperturbed Hamiltonian, without H_{int}, and taking into account the one-particle energies in the neighboring odd-mass nuclei, corrected for zeroth order rotational contributions, the lowest states in the odd-odd nucleus have $K=|\Omega_p\pm\Omega_n|$ and energy [26,28,29]

$$E_{pn}=E_p+E_n-2\frac{\hbar^2}{2\mathcal{J}}\Omega_<\delta_{K,|\Omega_p-\Omega_n|}+E_{\text{GM}}\delta_{\Sigma 0},$$

where $\Omega[Nn_3\Lambda]$ are the Nilsson asymptotic eigenstates in the odd-mass neighboring nuclei, with E_p and E_n their experimental excitation energies, $\Omega_<=\frac{1}{2}(\Omega_p+\Omega_n+|\Omega_p-\Omega_n|)$ is the lowest value between Ω_p and Ω_n. As described by Gallagher and Moszkowski [27], the energy of the compound state lies higher when the spins of the two odd particles are coupled antiparallel $(\Sigma=0)$. Theoretical calculations of the magnitude of the E_{GM} interaction were made by Boisson *et al.* [29], who fitted the parameters of an effective residual interaction to the experimental values of the GM splitting. We adopted their theoretical values if available. From the experimental energy difference between the states $J^\pi=2^+$ at 55.03 keV and $J^\pi=3^+$ at 0.0 keV, taken as the doublet $\pi 1/2^-[541]\otimes\nu 5/2^-[523]$, the GM splitting intensity was calculated for this configuration $(E_{\text{GM}}=63\text{ keV})$. Where no calculation was available a mean value $(E_{\text{GM}}=120\pm100\text{ keV})$ was adopted. The effects of the rotation-particle (Coriolis) and of the rotational particle-particle interactions were neglected [26]. The pairing interaction was partially accounted for, from the experimental values of the one-particle excitation energies in the odd-mass neighboring nuclei. For $\mathcal{J}$ the Takahashi's rule was adopted [30]: the moment of inertia is greater in odd-mass (e-o,o-e) nuclei than in even-even (e-e) core nuclei, and the increase in odd-odd (o-o) nuclei is approximately the sum of the contributions from the odd particles (see Ref. [25], pp. 121, 206).

$$\mathcal{J}_{o\text{-}o}=\mathcal{J}_{o\text{-}e}+\mathcal{J}_{e\text{-}o}-\mathcal{J}_{e\text{-}e}.$$

The adopted parameters are reported in Table III. A total number of 72 states could be made. Only states with spin lower than 3 were reasonably excited in ϵ decay from the $J=0^+$ parent, except for the low-lying isomers. Three 0^- states, two 0^+, six 1^-, five 1^+, eight 2^-, and five 2^+ were predicted at less than 500 keV excitation energy. Greater excitation levels might be strongly mixed and coupled to anharmonic vibrations [31]. The comparison with the experimental levels is made in Table IV. We note some good agreements, e.g., for the $1^+(\pi 7/2^-[523]-\nu 5/2^-[523])$ level, predicted at 250 ± 50 keV and experimentally identified at 239 keV; and for the $1^+(\pi 7/2^-[523]-\nu 5/2^-[512])$, at 490 ± 170 keV, experimentally at 591 keV. The experimental level density is also correctly reproduced.

V. CONCLUSIONS

A coherent level scheme of the doubly odd ^{168}Lu nucleus was proposed from the study of the $(\epsilon+\beta^+)$ decay of ^{168}Hf. 39 levels were proposed, accounting for 107 of 119 observed γ transitions. The isomeric transition between the two low-lying isomers was probably identified to be 202.81 $\pm$0.13 keV. Spin and parity assignments were discussed and deduced according to reasonable arguments.

TABLE IV. Experimental and calculated bandhead energy in ^{168}Lu. Uncertainties in the last significant digits are given in parentheses after the corresponding values.

Config.[a]	Bandhead energy (keV) E_{exp}[b]	E_{calc}[c]	A_{calc} (keV)	E_{GM} (keV) Exp.	Calc.[d]
$6^- AZ$	(−203)	−110(50)	10.1(11)		174
$3^+ CZ$	0	0	7.5(5)	63[e]	
$1^+ AY$	(8)	−100(100)	6.6(5)		f
$2^+ BY$	(16)	20(50)	6.2(3)		89
$2^+ CZ$	55	55	7.5(5)	63[e]	
$1^+ FZ$	239	250(90)	9.6(8)		154
$1^+ FX$	591	490(170)	12.0(12)		f
$2^- CY$	(36)	30(110)	5.4(3)		f
$2^- AW$	(38)	40(100)	10.9(17)		83
$2^- BZ$	57	100(50)	9.2(7)		f
$2^- BX$	117	110(130)	11.4(12)		237
$2^- DV$		250(220)	13.0(19)		f
$1^- AX$	101(147)	−30(80)	12.8(18)		106
$1^- AZ$	152	17(5)	10.1(11)		174
$0^- DZ$	158	30(140)	10.5(11)		f
$1^- BW$		160(150)	9.9(12)		216
$1^- BV$		180(150)	11.1(13)	192[g]	94
$0^- BV$		260(150)	11.1(13)	192[g]	94
$2^+ CX$	214	130(130)	8.9(7)		26
$1^+ CW$	223	170(180)	8.0(8)		f
$1^+ CV$	225	190(150)	8.7(8)		49
$2^+ EZ$		240(50)	6.9(4)		106
$2^+ CW$		300(180)	8.0(8)		f
$0^+ DY$	(168,173)	200(100)	6.7(5)		f
$0^+ CV$	(190,192)	230(150)	8.7(8)		49
$0^- DX$		320(170)	13.4(18)		169
$1^- DW$		340(190)	11.4(18)		f
$2^- BW$		380(150)	9.9(12)		216
$2^- AT$		380(100)	11.6(15)		163
$2^- EY$		410(60)	5.06(23)		f
$1^- FY$		420(90)	6.4(3)		123

[a]See Table III for key to ⟨⟨AZ⟩⟩ configuration.
[b]Proposed experimental attribution; parentheses denotes weak identifications.
[c]$E_{calc}=E_{pn}-E_{pn}(3^+CZ)$.
[d]From Ref. [29]; our definition for E_{GM} corresponds to the absolute value of that in the reference.
[e]Calculated from 3^+-2^+CZ energy difference.
[f]Not available in Ref. [29]: $E_{GM}=120(100)$ keV mean value assumed.
[g]Experimental value from Ref. [32] disagrees with theoretical one from Ref. [29].

Further investigations would be needed to firmly establish the structure of this nucleus: our assignments are based mainly on systematic trends. Conversion-electron measurements might be carried out at better resolution, but our method of production, in the continuous separation setup, is not adequate to produce sources for out-of-beam measurements. High-spin experiments would be feasible to extend the range of known levels by exciting rotational bands.

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[1] V. S. Shirley, Nucl. Data Sheets **71**, 261 (1994).
[2] B. Harmatz and T. H. Handley, Nucl. Phys. **81**, 481 (1966).
[3] Y. Y. Chu and J. Reednick, Phys. Rev. C **2**, 310 (1970).
[4] A. Charvet, R. Chéry, Do Huu Phuoc, R. Duffait, A. Emsallem, and G. Marguier, Nucl. Phys. **A197**, 490 (1972).
[5] E. N. Shurshikov and N. V. Timofeeva, Nucl. Data Sheets **67**, 43 (1992).
[6] F. W. N. de Boer, P. F. A. Goudsmit, P. Koldwijn, and B. Meyer, Nucl. Phys. **A225**, 317 (1974).
[7] C. M. Baglin, Nucl. Data Sheets **77**, 125 (1996).
[8] J. Tréherne, J. Vanhorenbeeck, and J. Valentin, Nucl. Phys. **A131**, 193 (1969).
[9] M. Blann and H. K. Vonach, Phys. Rev. C **28**, 1475 (1983); Lawrence Livermore National Laboratory Report No. UCRL-19614, 1982.
[10] D. Trubert, M. Hussonnois, L. Brillard, V. Barci, G. Ardisson, Z. Szeglowski, and O. Constantinescu, Radiochimica Acta **69**, 149 (1995).
[11] R. Gunnink and J. B. Niday, Lawrence Livermore National Laboratory (LLNL) Report No. UCRL-51061, Vols. I–IV, 1971, 1972; R. Gunnink and W. D. Ruther, LLNL Report No. UCRL-52971, 1980; R. Gunnink, W. D. Ruther, and J. B. Niday, LLNL, Nuclear Chemistry Division, Annual Report No. FY 82, UCAR-10002-82/1, 1983.
[12] R. S. Hager and E. C. Seltzer, Nucl. Data, Sec. A **4**, 1 (1968).
[13] Y. Y. Chu, in Proceedings of the International Conference on the Properties of Nuclei Far From Stability, Leysin, Switzerland, 1970, Report No. CERN-70-50, Vol. 2, p. 931.
[14] C. Ekström, W. Hogervorst, B. Ingelman, and G. Wannberg, Phys. Scr. **10**, 301 (1974).
[15] R. O. Wilson and M. L. Pool, Phys. Rev. **118**, 227 (1960).
[16] E. R. Merz and A. A. Caretto, Jr., Phys. Rev. **122**, 1558 (1961).
[17] A. A. Bykov, V. D. Vitman, Yu. V. Naumov, S. Yu. Orlov, and V. K. Tarasov, Izv. Akad. Nauk SSSR, Ser. Fiz. **43**, 574 (1981).
[18] R. Arlt, Z. Malek, G. Musiol, G. Pfrepper, and H. Struzny, Izv. Akad. Nauk. SSSR, Ser. Fiz. **33**, 1218 (1969) [Bull. Acad. Sci. USSR, Phys. Ser. **33**, 1133 (1970)].
[19] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[20] R. Arlt, K. Y. Gromov, Z. Malek, G. Musiol, G. Pfrepper, and H. Struzny, Izv. Akad. Nauk. SSSR, Ser. Fiz. **34**, 713 (1970) [Bull. Acad. Sci. USSR, Phys. Ser. **34**, 2281 (1971)].
[21] J. K. Tuli, ENSDF, A Manual for Preparation of Data Sets, National Nuclear Data Center, Report No. BNL-NCS-51655-Rev. 87, 1987.
[22] A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North Holland, Amsterdam, 1959).
[23] L. Grodzins, Annu. Rev. Nucl. Sci. **18**, 291 (1968).
[24] V. S. Shirley, Nucl. Data Sheets **43**, 688 (1984); **58**, 871 (1989); **64**, 505 (1991); **66**, 69 (1992); **75**, 377 (1995); M. A. Lee, *ibid.* **53**, 507 (1988); T. W. Burrows, *ibid.* **56**, 313 (1989); R. G. Helmer, *ibid.* **59**, 1 (1990); **72**, 83 (1994); L. K. Peker, *ibid.* **65**, 439 (1992); A. O. Macchiavelli and E. Browne, *ibid.* **69**, 903 (1993).
[25] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2.
[26] H. T. Motz *et al.*, Phys. Rev. **155**, 1265 (1967).
[27] G. J. Gallagher and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).
[28] S. B. Burson, P. J. Daly, P. F. A. Goudsmit, and A. A. C. Klasse, Nucl. Phys. **A204**, 337 (1971).
[29] J. P. Boisson, R. Piepenbring, and W. Ogle, Phys. Rep. **26**, 99 (1976).
[30] G. Sharff-Goldhaber and K. Takahashi, Izv. Akad. Nauk. SSSR, Ser. Fiz. **31**, 38 (1967) [Bull. Acad. Sci. USSR, Phys. Ser. **31**, 42 (1967)].
[31] R. K. Sheline, J. Kvasil, and P. C. Sood, Phys. Rev. C **44**, 2499 (1991).
[32] R. W. Hoff *et al.*, Phys. Rev. C **54**, 78 (1996).