# Excited states in $^{168}$Yb from electron-capture decay of $^{168}$Lu$^{m}$ ($T_{1/2}$=6.7 min)

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The electron-capture decay of the $^{168}$Lu$^{m}$ ($T_{1/2}$=6.7 min, $J^{\pi}=3^{+}$) isomer was studied with high purity sources, obtained by using a new radiochemical method consisting of fast continous on-line separation of reaction products. A complex spectrum composed of about 200 $\gamma$ rays was observed. From these, 162 transitions were assigned to a level scheme of 39 excited levels of $^{168}$Yb, primarily by $\gamma$-$\gamma$ coincidence spectroscopic measurements. About 60 transitions were placed for the first time and >90% of the decay intensity was clearly identified. The structure of the levels directly fed by the electron-capture decay was reviewed as particle-hole excitations of the core. [S0556-2813(99)01308-4]

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## I. INTRODUCTION

Low energy excitation levels of well-deformed even-even nuclei such as $^{168}$Yb have been extensively studied both theoretically and experimentally. They have always been the main application field for collective deformed models [1]. A lot of experimental work, as well as transfer reactions, inelastic scattering, Coulomb excitation, heavy ion (HI) reactions, and decay measurements, was carried out (see Ref. [2] and references therein). Nevertheless, decay studies remain incomplete and should be reviewed, essentially owing to the existence of two isomers in the $^{168}$Lu odd-odd parent, a $J^{\pi}=(6^{-})$ ground state (g.s.) ($T_{1/2}$=5.5 min) and a $J^{\pi}=3^{+}$ excited state ($T_{1/2}$=6.7 min) at ≈200 keV energy. It was already noticed that the isomer activity ratio depends on the manner of producing the $^{168}$Lu parent. Sources obtained by $^{168}$Hf decay were shown to excite mainly the longest half-life isomer [3], identified as an excited state, while sources obtained by direct nuclear reactions [say $^{168}$Tm($\alpha,n$)] contained both isomers [4,5].

In carrying out a research program for the production and chemical separation of transactinide elements ($Z\geqslant 104$) we tested our separation facility RACHEL (rapid aqueous chemistry apparatus for heavy elements) [6] by producing the homologous elements in Mendeleiev's table (Hf, Ta, ...) of the corresponding transactinides (Rf, Db, ...). Details of the separation method will be given later (Sec. II). Mass chains in the range $A=164$–169 were obtained; some decay analyzes are still in progress. In this paper we report the study of the $^{168}$Lu→ $^{168}$Yb decay and the development of a new radiochemical method to obtain high purity sources. A paper on $^{168}$Hf decay has already been published [7].

Beta decay involves the transformation of only a single nucleon and the reduced transition probabilities, usually expressed in the form of log $ft$ values, provide valuable information about the relative spin and parity of the parent and daughter states. These data seldom point to unique Nilsson orbital assignments. One reason for this is that observed transitions are primarily either allowed hindered ($\Delta I=0,\pm 1$, with no parity change) or nonunique first forbidden ($\Delta I=0,\pm 1$, with a parity change), and these two transition types have comparable transition probabilities ($6<\log ft<8.5$). On the other hand, in some cases $\log ft\leqslant 5$ and the transition is unquestionably allowed unhindered (au). It must conserve all Nilsson quantum numbers ($Nn_z\Lambda$). It was shown that only two orbital pairs ($\nu 7/2^{-}[514]\leftrightarrow\pi 9/2^{-}[514]$) and ($\nu 5/2^{-}[523]\leftrightarrow\pi 7/2^{-}[523]$) exist in the rare-earth region which could give rise to such transitions. The daughter states must contain significant components of the corresponding configurations. In addition these states usually lie above the pairing gap, and must be described as particle-hole excitations of the core. We made an attempt to analyze our data according to such an interpretation.

## II. EXPERIMENTAL METHODS

The experimental setup for producing $^{168}$Hf sources has been described elsewhere [7] and will be summarized below. Pure (>99%) $^{156}$Gd targets were bombarded with $^{16}O^{7+}$ 100-MeV ions at IPN (Institut de Physique Nucléaire) tandem facility at Orsay. Target and window energy losses were tuned to obtain the cross-section maximum of the $^{156}$Gd($^{16}$O,4$n$)$^{168}$Hf reaction.

Pure lanthanum sources were separated from decay products with the RACHEL apparatus. Basically the reaction products were collected with a helium jet facility, charged with KCl aerosols, brought to the chemical reaction vessel, and dissolved in HF. There they might form anionic or cationic complexes. Three different resin separation columns, in serial setup, retained anionic (or cationic) complexes, while unlike species passed through. The first column retained cations (lanthanides) issued from decays during transfer time, the second one retained anions ($[HfF_6]^{2-}$) and was used as a source of pure hafnium, and the third one retained the cations ($Lu^{3+}$) issued from the hafnium decay in the second column. In the present experiment the last column was continously eluted and measured in direct and coincidence countings.

A three-detector coincidence setup was used, composed of a 20-cm$^{2}$-area, 0.5-keV full-width-at-half-maximum

 

(FWHM) resolution at 122 keV, HPGe (high purity germanium) planar detector; a 40% relative efficiency, 1.75-keV FWHM at 1.33 MeV, and a 20%, 1.89-keV FWHM, coaxial detectors, at 90° to each other in orthogonal planes.

Single-$\gamma$-ray spectra were recorded on a multichannel analyzer and processed with the computer code GAMANAL [8]. About $5.8\times10^6$ coincidence events were stored on tape and analyzed off line in bidimensional matrices between any two detectors. Spectroscopic data were obtained with computer codes of the ENSDF (evaluated nuclear structure data files) package from NNDC (National Nuclear Data Center).

## III. RESULTS

### A. $\gamma$ spectrum and level scheme

Energies and intensities were measured with proper detector calibrations using standard reference sources. Corrections for coincidence summing were applied if needed. Here 162 out of 177 identified $\gamma$ lines (Table I) were assigned to a $^{168}$Yb scheme of 39 excited levels (Table II). The assignments were made first by coincidence relations, second by agreement with energy level differences. Some transitions might be multiply placed into the level scheme and a few levels were proposed only on account of energy difference relations. Some placements (about 60) are reported for the first time and were mostly confirmed by coincidence measurement. Some examples are reported in Fig. 1: e.g., a 201.0-keV transition between the 2404.9- and 2204.0-keV levels was firmly established by coincidence measurements; a new level was proposed at 2055.9 keV to account for the coincidence between the 1071.9-keV and 148.2-keV transitions.

Multipolarity assignments were made according to the following arguments in increasing order of importance.

(i) Primarly, they were made on the basis of the known $K$-electron conversion coefficients measured by Charvet *et al.* [4], compared with the theoretical values [9]. The $\alpha_{K\mathrm{expt}}$ values of the reference were multiplied by a factor of 1.25 according to a reanalysis of the experimental data. The new normalization was adopted on the basis of the assignment of pure $E2$ character to the single 298.8-keV transition. The other transitions previously used for normalization, and assumed to be pure $E2$ in Ref. [4], are multiple (strong 198.9+201.0 keV+ some weak components and 979.4 +984.0 keV) or may be mixed ($M1+E2$: 884.8 and 896.3 keV; see discussion in Sec. IV). With the new choice good agreement was obtained, e.g., for the single $\gamma$ rays 1083.6 and 1219.9 keV, assigned to be pure $E2$ transitions within experimental uncertainties and confirmed unmixed from level scheme.

(ii) Additional secondary multipolarity assignments were made according to level scheme and comparison of the theoretical asymmetry $A=W(180°)/W(90°)-1$ from directional correlation $W(\theta)$ for assumed known $I_0 \underset{\gamma_1}{\rightarrow} I_1 \underset{\gamma_2}{\rightarrow} I_2$ [10], with the corresponding experimental value from coincidence intensity ratio for $\gamma_2$ and $\gamma_1$ detected at 180° and 90° with respect to the gating transition.

(iii) As usual only low order possible multipolarities were considered for unmeasured values, according to Weisskopf's single-particle estimates [11].

The assignments reported in the review data of Ref. [2] were generally found to be in agreement with our analysis, except in some minor cases.

Spin assignments were deduced from comparison of assigned multipolarities and existing transitions depopulating each level. Additional assignments for levels directly populated in $\beta$ decay were made accounting for selection rules for $\log ft<7$ from a $3^+$ parent state, which permit only allowed or first-forbidden transitions $\Delta I=0$, 1, so $I=2-4$.

### B. Isomeric states in $^{168}$Lu

It has already been reported that $^{168}$Lu sources produced by $^{168}$Hf decay are mainly composed of the 6.7-min isomer [3,5]. In a preceding paper [7] we proposed the existence of a 202.8-keV isomeric transition (IT) of $0.86\pm0.21\,\%$ of the total decay, from the observation of a weak $\gamma$ transition in the $^{168}$Hf decay spectrum. This transition is strongly masked in $^{168}$Lu decay owing to a multiplet around 200 keV. A weak $\gamma$ ray is possible at $202.5\pm0.4$ keV, with an intensity of $1.2\pm0.3$ relative units (% of the intensity of the 896-keV $\gamma$). This $\gamma$ does not appear in coincidence spectra, as expected. In these units the total intensity of the IT transition ($E3$ with theoretical conversion coefficient $\alpha_{\mathrm{total}}=1.76$ [9] and absolute normalization to 100 decays $N=0.164\pm0.021$) should be $0.54\pm0.15\,\%$ of the decay. The agreement with the previous suggestion seems fair, but some other discrepancies still emerge. First, the main $\gamma$'s excited in $^{168}$Lu$^g$ decay do not appear in our spectra; second, other $\gamma$'s assigned to g.s. decay appear with the wrong intensities or may be assigned to the $^{168}$Lu$^m$ decay and placed elsewhere in the level scheme. So either the existence of a low mixture of g.s. decay in isomeric decay may be questionable, or the $\gamma$ rays of g.s. decay are under the detection limit. Taking a conservative view, only an upper limit for the IT intensity may be proposed $I_{\mathrm{IT}}<0.8\%$ (at 90% C.L.), still lower than the value previously proposed ($I_{\mathrm{IT}}<5\%$ [5], $I_{\mathrm{IT}}<4.5\%$ [3]).

### C. $\epsilon+\beta^+$ decay

From total intensity imbalances at each level a decay scheme was established. We made the hypothesis that no direct branch was feeding the g.s. No branch was reported if $I_{(\epsilon+\beta^+)}<1\%$, except for high energy levels with no incoming $\gamma$'s or if the $(\Delta I/I)_{(\epsilon+\beta^+)}>50\%$. The decay scheme is reported in Figs. 2–6.

As discussed later, only lower limits can be settled for the transition decays to levels below 1.2 MeV. From theoretical considerations, according to the rotational model, the leading order intensity for λ-multipole radiation must be inversely proportional to the square of a Clebsch-Gordan coefficient (see relation 4.91, p. 58 in Ref. [1])

$$ft(\lambda;I_i^\pi K_i\rightarrow I_f^\pi K_f)=\langle I_iK_i\lambda(K_i-K_f)|I_fK_f\rangle^{-2}|M|^{-2},$$

where $M$ is an intrinsic matrix element independent of spins. So the $ft^{-1}$'s for the allowed ($\lambda=1$) transitions to the levels

TABLE I. $\gamma$(168Yb) from $(\epsilon+\beta^{+})\,^{168m}$Lu decay. Standard uncertainties on the last digits are given in parentheses after the values. Unassigned $\gamma$'s have empty placements. Relative photon intensities are normalized to 100 for the 896.261-keV transition; for absolute intensities per 100 decays multiply by 0.164(21). Values in parentheses are probable (weak) measured assignments; values in brackets are deduced from level scheme. Limits on multipole mixing were deduced from $\alpha_{K\mathrm{expt}}$ except otherwise stated.

| $E_\gamma$ (keV) | $I_\gamma$ (relative) | Multipolarity | Placement (from level) |
|---|---|---|---|
| 17.7(5) | 0.50(25) | | |
| 24.0(5) | 1.2(6) | $[M1(+E2<13\%)]$ | 2427.97 |
| 27.1(5) | 0.50(25) | $[E1]$ | 1480.00 |
| 53.2(5) [a] | $<1$ | | 2064.96 |
| 68.0(5) [a] | $<0.3$ | | 2203.99 |
| 74.0(5) [a] | $<0.4$ | | 1233.44 |
| 84.0(6) | 0.24(14) | $[M1+E2]$ | 1067.15 |
| 87.77(3) | 82(12) | $E2$ | 87.764 |
| 89.6(4) | 0.46(16) | $[E1]$ | 1480.00 |
| 99.60(3) | 3.1(5) | $[M1+E2]$ | 1551.33 |
| 104.8(9) | 0.08(7) | $[M1+E2]$ | 1171.38 |
| 122.95(6) | 1.25(21) | $[M1+E2]$ | 1674.20 |
| 130.90(6) | 1.30(23) | $[M1+E2]$ | 1302.41 |
| 147.08(8) [b] | 0.61(25) | | 2064.96 |
| | | | 2158.54 |
| 148.16(4) | 4.2(7) | $[M1+E2]$ | 2203.99 |
| 166.3(5) | 0.22(9) | | 1233.44 |
| 176.3(3) [a] | 0.22(10) | | 1407.9 |
| 187.34(19) | 0.43(11) | $[E2]$ | 1171.38 |
| 191.24(23) | 0.49(14) | | 2255.95 |
| 198.90(3) | 190(30) | $E2$ | 286.60 |
| 200.2(8) [a] | 3.4(12) | $[M1+E2]$ | 2255.95 |
| 201.01(15) | 11.2(20) | $[M1+E2]$ | 2404.86 |
| 202.5(4) [d] | 1.2(3) | $[E3]$ | |
| 222.55(17) | 0.90(19) | $[E2]$ | 1674.20 |
| 224.15(17) | 0.89(18) | $[M1+E2]$ | 2427.97 |
| 231.3(5) | 0.17(9) | | 2203.99 |
| 235.6(5) | 0.23(16) | $[E2]$ | 1302.41 |
| 246.33(4) | 5.2(8) | $[M1+E2]$ | 2404.86 |
| 248.7(3) | 0.47(15) | | 1551.33 |
| 269.48(11) [b] | 1.21(23) | | 2404.86 |
| | | | 2427.97 |
| 271.4(3) | 0.25(11) | $[M1+E2]$ | 2475.23 |
| 280.5(3) | 0.39(10) | $[M1+E2]$ | 1451.76 |
| 283.5(5) | 0.21(11) | | 2255.95 |
| 294.90(9) | 2.0(4) | | 2475.23 |
| 298.77(4) | 12.6(20) | $E2$ | 585.36 |
| 300.2(8) | 0.26(14) | | 1472.8 |
| 313.5(6) | 0.19(10) | | |
| 331.80(13) | 1.4(3) | | |
| 339.2(4) | 0.49(18) | | 2404.86 |
| 347.1(3) | 0.45(20) | | |
| 348.99(4) | 9.5(15) | $E2(+M1<35\%)$ | 2404.86 |
| 372.17(18) | 1.3(3) | | 2427.97 |
| 375.0(4) | 0.53(19) | | 1972.84 |
| 380.11(6) | 4.5(7) | $[M1+E2]$ | 1551.33 |
| 384.80(7) | 6.9(11) | $E2(+M1<37\%)$ | 1451.76 |
| 393.50(7) | 5.1(8) | $[M1+E2]$ | 2404.86 |
| 405.9(5) [b] | 0.34(15) | | 1472.8 |
| | | | 1390.11 |
| 449.7(4) | 0.65(22) | | 2180.33 |
| 467.90(5) | 6.4(11) | $M1(+E2<70\%)$ | 1451.76 |
| 473.6(4) | 0.73(24) | | 2203.99 |
| 479.3(8) | 0.31(16) | | 1650.65 |
| 484.32(18) [b] | 1.6(3) | | 1551.33 |
| | | | 2158.54 |
| 497.40(21) | 0.8(4) | | 1730.67 |
| 521.7(7) | 0.30(17) | | 1972.84 |
| 530.1(7) [b] | 1.2(5) | | 1597.87 |
| | | | 2203.99 |
| 550.67(23) | 1.3(3) | | |
| 560.0(5) | 0.46(22) | | 2158.54 |
| 567.41(15) | 2.3(5) | | 1551.33 |
| 583.50(21) | 1.6(4) | $(E1)$ | 1650.65 |
| 586.4(9) | 0.34(20) | | 1171.38 |
| 605.8(3) | 1.7(5) | $[E1]$ | 2203.99 |
| 607.22(9) | 8.5(14) | $[M1+E2]$ | 2158.54 |
| 621.6(8) | 0.4(2) | | 2011.42 |
| 652.75(9) | 5.2(9) | $[M1+E2]$ | 2203.99 |
| 659.0(5) | 0.46(25) | | 2255.95 |
| 674.6(5) [b] | 0.9(4) | | 2064.96 |
| | | | 2404.86 |
| 683.4(6) | 0.63(20) | | 2135.38 |
| 697.6(4) | 0.93(25) | $[E2]$ | 984.00 |
| 706.83(17) | 3.1(6) | $[M1+E2]$ | 2158.54 |
| 717.28(20) | 2.5(5) | $E2(+M1<47\%)$ | 1302.41 |
| 723.4(7) | 0.49(23) | | 2203.99 |
| 730.73(7) | 9.5(15) | $(E2)$ | 2404.86 |
| 752.33(8) | 8.2(13) | $[M1+E2]$ | 2203.99 |
| 768.4(7) | 0.62(23) | | 2158.54 |
| 780.61(5) | 26(4) | $E2(+M1<44\%)$ | 1067.15 |
| 804.90(16) | 0.94(25) | | 1390.11 |
| 806.95(11) | 4.8(11) | $[E1]$ | 2404.86 |
| 830.3(4) | 1.7(4) | | 2427.97 |
| 832.1(3) | 1.2(4) | | 2135.38 |
| 853.57(4) | 27(4) | $E2(+M1<89\%)$ | 2404.86 |
| 856.3(10) | 0.8(3) | | 2158.54 |
| 884.8(5) | 1.0(5) | | 2055.88 |
| 884.807(24) | 84(13) | $E2(+M1<39\%)$ | 1171.38 |
| 887.6(5) | 0.9(4) | | 1472.8 |
| 896.261(24) | 100 [e] | $E2(+M1<39\%)$ | 984.00 |
| 901.6(10) | 7.6(13) | $[M1+E2]$ | 2203.99 |
| 924.93(24) | 2.3(5) | $[E1]$ | 2404.86 |
| 944.42(25) | 1.8(6) | | 2011.42 |
| 947.85(12) | 2.4(10) | | 2427.97 |
| 953.3(3) [b] | 2.0(5) | | 2255.95 |
| | | | 2404.86 |
| 964.19(15) | 4.7(8) | | 2135.38 |

TABLE I. (*Continued*).

| $E_\gamma$ (keV) | $I_\gamma$ (relative) | Multipolarity | Placement (from level) |
|---|---|---|---|
| 979.379(24) | 128(20) | $E2(+M1<80\%)$ | 1067.15 |
| 983.99(4) | 78(13) | $E2$ | 984.00 |
| 987.34(15) | 8.2(14) | $[M1+E2]$ | 2158.54 |
| 988.96(18) | 6.3(11) | $[M1+E2]$ | 2055.88 |
| 998.7(7) | 0.6(3) | | 2064.96 |
| 1013.0(6) | 0.58(22) | $(M2)$ | 1597.87 |
| 1015.86(7) | 11.4(17) | $E2(+M1<87\%)$ | 1302.41 |
| 1027.44(20) | 2.8(6) | | 2011.42 |
| 1032.61(4) | 57(8) | $M1(+E2<79\%)$ | 2203.99 |
| 1066.8(9) [a] | <0.2 | | 1154.6 |
| 1068.0(9) | 1.3(8) | | 2135.38 |
| 1071.9(10) [a] | <1 | | 1159.95 |
| 1071.94(5) | 15.7(25) | $(M1+E2)$ | 2055.88 |
| 1083.58(3) | 41(7) | $(E2)$ | 1171.38 |
| 1084.9(4) | 0.8(4) | | 2255.95 |
| 1089.0(10) | 0.3(3) | | 1674.20 |
| 1091.58(19) | 3.0(7) | | 2158.54 |
| 1102.9(3) | 1.9(4) | $(E0+E2)$ | 1390.11 |
| 1113.6(8) [b] | 0.5(4) | | 2415.5 |
| | | | 2180.33 |
| 1136.83(4) | 84(13) | $45\%M1+55\%E2$ [f] | 2203.99 |
| 1144.9(6) | 0.6(3) | | 1233.44 |
| 1151.0(9) | 0.49(20) | | 2135.38 |
| 1159.2(7) [b] | <0.2 | | 1159.95 |
| 1165.21(16) | 4.4(7) | $[M1+E2]$ | 1451.76 |
| 1188.31(21) | 0.8(7) | | 2255.95 |
| 1191.2(8) | 1.3(4) | | 1279.0 |
| 1193.4(3) | 3.2(6) | | 1480.00 |
| 1219.94(5) | 69(11) | $E2$ | 2203.99 |
| 1231.3(4) [b] | 1.0(6) | | 1231.3 |
| 1233.46(7) [c] | 3(3) | $[E2]$ | 1233.44 |
| | 17(3) | $(M1+E2)$ | 2404.86 |
| 1256.36(12) | 4.9(8) | $(E2)$ | 2427.97 |
| 1264.68(5) | 14.6(23) | | 1551.33 |
| 1279.0(4) | 0.6(3) | | 1279.0 |
| 1302.4(3) | 1.6(4) | $[E2]$ | 1390.11 |
| 1311.27(11) | 5.9(9) | $(E1)$ | 1597.87 |
| 1320.12(18) [a] | 3.0(6) | | 1407.9 |
| 1337.65(5) | 25(4) | $E2(+M1<60\%)$ | 2404.86 |
| 1360.7(6) | 1.3(3) | | 2427.97 |
| 1363.90(4) | 23(4) | $E2(+M1<50\%)$ | 1451.76 |
| 1380.0(6) | 0.8(3) | | 2364.5 |
| 1387.43(12) | 6.8(11) | $(M1+E2)$ | 1674.20 |
| 1392.19(13) | 5.0(9) | $[E1]$ | 1480.00 |
| 1420.79(5) | 62(10) | $M1(+E2<60\%)$ | 2404.86 |
| 1434.4(3) | 1.7(3) | | |
| 1439.1(5) | 0.8(3) | | |
| 1445.5(6) [a] | 0.8(3) | | 2427.97 |
| 1463.47(10) | 12.4(20) | $(E2)$ | 1551.33 |
| 1510.00(13) | 5.4(9) | | 1597.87 |
| 1516.7(6) | 0.83(25) | | 1604.5 |
| 1521.1(6) | 0.76(22) | | |
| 1573.0(20) | 0.5(5) | | 2158.54 |
| 1594.2(4) | 1.4(3) | | 2180.33 |
| 1605.2(20) | 0.2(1) | | 1604.5 |
| 1619.0(10) | <0.4 | | 2203.99 |
| 1622.2(7) | 0.69(20) | | |
| 1631.2(4) | 1.9(4) | | 1917.88 |
| 1642.1(12) | 0.44(17) | | 1730.67 |
| 1686.3(3) | 0.2(2) | | 1972.84 |
| 1711.8(18) | 0.31(18) | | |
| 1724.6(7) | 0.84(22) | | 2011.42 |
| 1730.8(6) [a] | 0.6(3) | | 1730.67 |
| 1779.5(8) | 0.44(19) | | 2364.5 |
| 1793.5(8) | 0.52(24) | | |
| 1848.74(25) | 2.9(5) | | 2135.38 |
| 1853.7(8) | 0.78(23) | | |
| 1871.8(4) | 1.9(4) | | 2158.54 |
| 1894.1(10) | 0.36(21) | | 2180.33 |
| 1917.28(10) | 10.1(16) | | 2203.99 |
| 1967.7(14) | 0.6(3) | | 2055.88 |
| 1969.5(5) | 5.3(11) | | 2255.95 |
| 1977.6(9) | 0.69(21) | | 2064.96 |
| 2047.6(4) | 1.9(4) | | 2135.38 |
| 2070.9(4) | 2.0(4) | | 2158.54 |
| 2093.1(4) | 1.9(4) | | 2180.33 |
| 2116.24(20) | 11.7(22) | | 2203.99 |
| 2118.1(10) | 1.4(8) | | 2404.86 |
| 2128.7(4) | 1.6(3) | | 2415.5 |
| 2141.39(8) | 21(3) | | 2427.97 |
| 2168.4(5) | 1.0(3) | | 2255.95 |
| 2187.9(7) | 0.86(23) | | 2475.23 |
| 2276.8(4) | 1.7(4) | | 2364.5 |
| 2317.18(24) | 2.7(6) | | 2404.86 |
| 2336.5(11) | 0.9(3) | | |
| 2340.6(11) | 0.6(3) | | 2427.97 |
| 2358.4(8) [a] | 0.51(16) | | 2645.0 |

[a] Uncertain placement.
[b] Multiply placed, undivided intensity.
[c] Multiply placed, intensity suitably divided.
[d] Possible isomeric transition.
[e] Normalization value.
[f] $|\delta|=1.1(5)$ from $\alpha_{K\mathrm{expt}}=0.034(6)$ measurement [4].

TABLE II. $^{168}$Yb levels.

| $E$(level) | $J^{\pi}$ | $T_{1/2}$ [a] | Comments |
|---|---|---|---|
| 0.0 | $0^+$ | stable | b |
| 87.764(25) | $2^+$ | 1.47(3) ns | b |
| 286.60(3) | $4^+$ | | b |
| 585.36(5) | $6^+$ | | b |
| 984.00(3) | $2^+$ | 1.03(10) ps | c |
| 1067.15(3) | $3^+$ | | c |
| 1154.6(9) [d] | $(0^+)$ | | e |
| 1159.95(24) [d] | $(1^-)$ | | f |
| 1171.38(3) | $4^+$ | | c |
| 1231.3(4) [d] | $(1^-)$ | | f |
| 1233.44(7) | $2^+$ | <4 ps | e |
| 1279.0(4) | $2^+$ | | |
| 1302.41(6) | $5^+$ | | c |
| 1390.11(12) | $4^+$ | | e |
| 1407.9(2) [d] | $(2^-)$ | | f |
| 1451.76(4) | $3^+$ | | g |
| 1472.8(4) | $(4^+)$ | | |
| 1480.00(9) | $3^-$ | | f |
| 1551.33(4) | $4^+$ | | g |
| 1597.87(7) | $(4^-)$ | | f |
| 1604.5(6) | $(2^+)$ | | |
| 1650.65(21) | $(3,4)^-$ | | f |
| 1674.20(5) | $5^+$ | | g |
| 1730.67(17) | $(2^+)$ | | |
| 1917.88(19) | $(2^+,3,4^+)$ | | |
| 1972.84(20) | (3,4) | | |
| 2011.42(6) | $(2^+,3,4^+)$ | | |
| 2055.88(4) | $(2^+,3^+)$ | | |
| 2064.96(18) | $(2^+,3,4^+)$ | | |
| 2135.38(9) | $(3^+,4^+)$ | | |
| 2158.54(5) | $4^+$ | | |
| 2180.33(18) | $4^+$ | | |
| 2203.99(4) | $4^+$ | <0.14 ns | $\pi1/2^-[541]+\pi7/2^-[523]$ |
| 2255.95(13) | $(3^+,4^+)$ | | |
| 2364.5(3) | $(4^+)$ | | |
| 2404.86(4) | $3^+$ | | $\pi1/2^-[541]+\pi5/2^-[532]$ |
| 2415.5(4) | (3,4) | | |
| 2427.97(6) | $(3^+)$ | | $\pi1/2^-[541]-\pi7/2^-[523]$ |
| 2475.23(19) | $(2^+,3,4^+)$ | | $(\pi1/2^-[541]-\pi5/2^-[532])$ |
| 2645.0(8) [d] | $(2^+,3,4)$ | | |

[a]From Ref. [2].
[b]$g$ band.
[c]$\gamma$ band.
[d]Doubtful or weakly excited level.
[e]$\beta$ band.
[f]Octupole band.
[g]$(\pi7/2^+[404]-\pi1/2^+[411])$ band.

at 984.0 keV ($I^{\pi}K=2^+2$), 1067.1 keV ($I^{\pi}K=3^+2$), and 1171.3 keV ($I^{\pi}K=4^+2$) of the $\gamma$ band must be in a 7:20:140 ratio. Already the most intense decay to the 984.0-keV level is experimentally hardly observed (only a lower limit log $ft>6.3$ can be proposed), so decays to higher levels should be still weaker.

Some discussion is needed on the experimental $\beta$ energies. End-point energies were measured by Merz and Caretto [12], in a radiochemical separation experiment on $^{168}$Hf $\rightarrow^{168}$Lu$\rightarrow^{168}$Yb decay chain, who found $1.2\pm0.1$ MeV for $^{168}$Lu and $1.7\pm0.1$ MeV for $^{168}$Hf; by Arlt *et al.* [3], in the same experimental setting, who found $1.5\pm0.3$ and $2.7\pm0.3$ MeV for $^{168}$Lu; and by Charvet *et al.* [5,4], in $^{168}$Lu $\rightarrow^{168}$Yb, who found $1.23\pm0.08$ MeV for $^{168}$Lu$^{g}$ decay and $1.47\pm0.10$ MeV for $^{168}$Lu$^{m}$ decay. From intensity imbalances the 2.7-MeV $\beta^+$ end point is poorly compatible with our data: no $\beta^+$ transitions of significant intensity were observed towards excited levels in the $950\pm300$ keV region, but $\approx10\%$ of the feeding is missing or uncertain. So weak feedings to levels in this region might be allowed by experimental data.

An intensity ratio $\epsilon/\beta^+\approx8$ between electron capture and $\beta^+$ emission was measured by Merz and Caretto [12], in rough agreement with the ratio $14\pm2$ deduced from level imbalance. Most of the intensity proceeds through two branches (in the ratio 1/2): a 3.5% branch, which may be identified with the measured 1.47-MeV end-point energy [4], and a 1.9% branch 224 keV lower, which corresponds almost exactly to the 1.2-MeV [12] end point and the 1.23-MeV [4] end point (but with the wrong assignment). So the assignments are still unclear.

From intensity imbalance at each level the total feedings were determined. Using the tables of Gove and Martin [13] we calculated log $ft$ values. They are also reported in Fig. 2. Two levels appear to share most of the decay. The level at 2204.0 keV, with 41% of the intensity, and a level at 2428.0 keV, with 37%. Indeed the latter is only an upper limit: it is based on the assumption that most of the intensity flows through the 24-keV transition to the 2404.9-keV level. Unfortunately the 24-keV $\gamma$ was observed only in coincidence spectra and its intensity is subject to a high uncertainty. A high conversion coefficient ($>38.1$, $M1$ with probably low $E2$ mixing) prevents a clear total intensity determination. So 37% is the total feeding to 2404.9+2428.0 keV levels. For the lower levels at 286.6, 984.0, 1067.1, and 1171.4 keV only a lower limit can be proposed (at 68% or $1\sigma$ confidence limit). It may correspond to the end-point energy of $2.7\pm0.3$ Mev observed by Arlt *et al.* [3].

## IV. DISCUSSION

Low energy levels in deformed even-even nuclei have been extensively described as collective states [1]. The experimental pairing gap is defined from the even-odd experimental separation energies [14],

$$\Delta_{eo}^{(N)}=-\frac{1}{4}[S_n(N-1,Z)-2S_n(N,Z)+S_n(N+1,Z)]$$

(=1041 keV) for neutrons, or

$$\Delta_{eo}^{(Z)}=-\frac{1}{4}[S_p(N,Z-1)-2S_p(N,Z)+S_p(N,Z+1)]$$

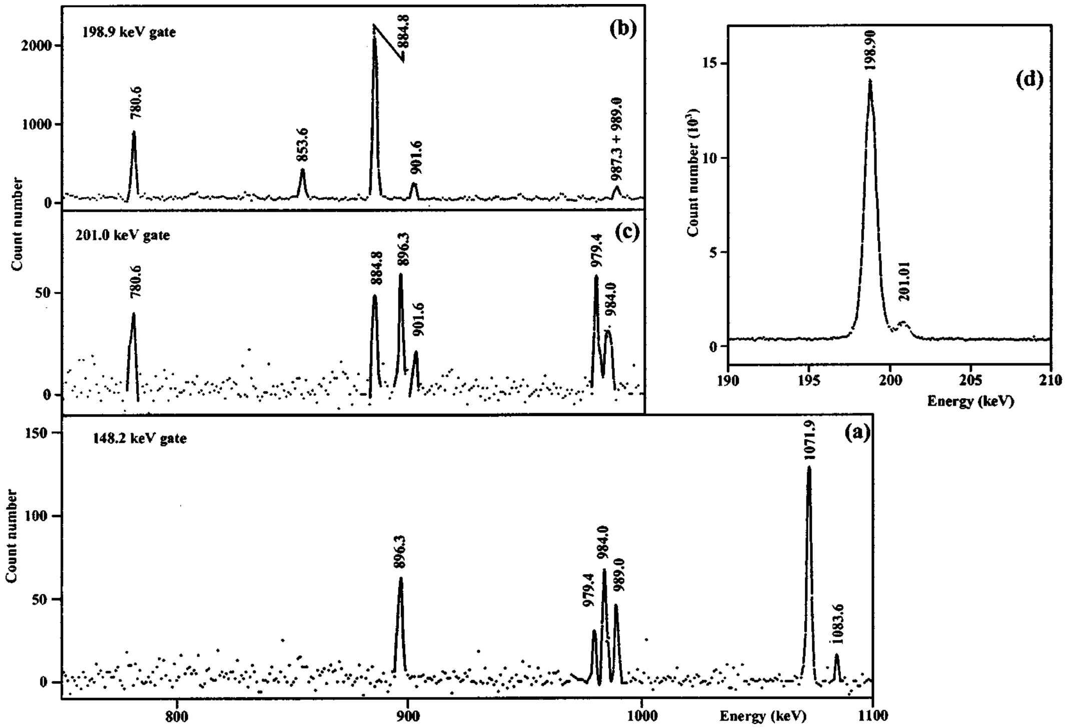


FIG. 1. Selected portions of coincidence related spectra. (a) 148.2-keV gate in the 750–1100 keV region. (b) 198.9-keV gate and (c) 201.0-keV gate in the 750–1000 keV region and the corresponding (d) total projection spectrum showing the gating transitions.

($=983$ keV) for protons, and $\Delta=0.8\Delta_{eo}$ to account for a weaker pair field in excited configurations [15]. The pairing gap appears lower for protons ($\Delta=786$ keV) than for neutrons ($\Delta=832$ keV). It may be compared with the semi-empirical value $\Delta=12/A^{1/2}=926$ keV. All states with excitation energy lower than $2\Delta\approx1.6$ MeV should be predominantly collective.

The classical ground ($K=0$), $\gamma$ ($K=2$), and $\beta$ ($K=0$) bands were extensively studied in this region. We must remark that the $\beta$ band is very poorly excited in the decay of $^{168}\mathrm{Lu}^m$. According to rotational model predictions,

$$B(E2;I_iK\rightarrow I_fK)=\langle I_iK20|I_fK\rangle^2|\langle K|M'(E2;0)|K\rangle|^2 \tag{4.1}$$

and

$$B(E2;I_i2\rightarrow I_f0)=2\langle I_i22-2|I_f0\rangle^2|\langle 0|M'(E2;-2)|2\rangle|^2 \tag{4.2}$$

for unmixed intraband (4.1) and interband ($K_i=2\rightarrow K_f=0$) (4.2) transitions, with quadrupole moments defined as

$$Q_0(K)=\frac{1}{e}\sqrt{\frac{16\pi}{5}}\langle K|M'E2;0)|K\rangle.$$

Experimental values of reduced transition probabilities were measured in Coulomb excitation experiments (reviewed in Ref. [2]) as

$$B(E2;00\rightarrow20)=5.77\pm0.04\ e^2\,\mathrm{b}^2,$$

$$B(E2;00\rightarrow22)=0.128\pm0.005\,e^2\,\mathrm{b}^2,$$

and will be compared with theoretical predictions.

### A. Generalized treatment

Reduced transition probabilties of interband $E2$ transitions were described quite generally by Mikhailov [16] by a mixing of rotational bands with different values of $K$ according to the generalized formula

$$B(E2;I_iK_i\rightarrow I_fK_f)=(1+\delta_{K_f0})\langle I_iK_i2-2|I_fK_f\rangle^2 \times|M_1+M_2(X_f-X_i)|^2, \tag{4.3}$$

with $X=I(I+1)$,

$$M_1=\langle K_i|M'(E2,2)|K_f\rangle-4(K_f+1)M_2,$$

and[1]

$$M_2=-\epsilon_\gamma\sqrt{\frac{15}{8\pi}}eQ_0(K_i),$$

where $\epsilon_\gamma$ is a spin-independent parameter related to interaction strength, and with the assumption $Q_0(K_i)=Q_0(K_f)$.

A polynomial least-squares fit of $\sqrt{B(E2;I_i2\rightarrow I_f0)}/\langle I_i22-2|I_f0\rangle$ versus $X_f-X_i$ must give a straight line. $\Delta I=1$ transitions are supposed to be unmixed (pure $E2$), because of the experimental $K/L$ conversion coefficient ratios,

[1]A minus sign was set in the definition of $M_2$ with respect to Ref. [1], formula 4.230, p. 159, to maintain compatibility.

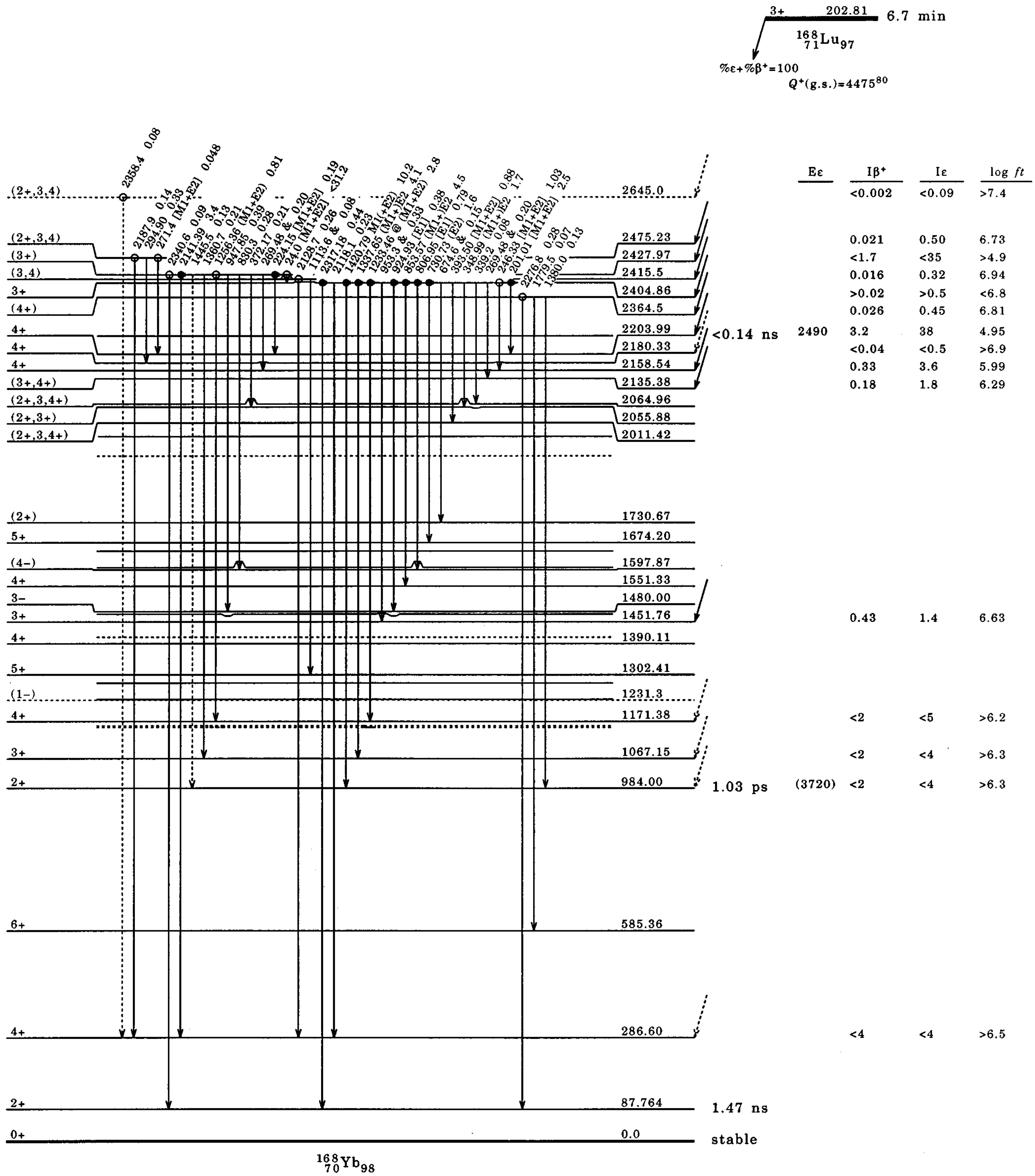


FIG. 2. $\beta$ decay scheme. @ Multiply placed: intensity suitably divided. & Multiply placed: undivided intensity given. Intensities: $I(\gamma+ce)$ per 100 parent decay. Dots mark observed true coincidences, open dots weak coincidences; dashed lines stand for uncertain placements. Parentheses denote weak assignments, square brackets deduced assignments.

which were supposed to be pure $E2$ [17], but they appear also compatible with an unvanishing $M1$ mixing ($K/L$ varies less than 20% from $E2$ to $M1$ for all transitions), so this hypothesis may be unrealistic. The $\alpha_{K\mathrm{expt}}$ values [4] are also compatible with $M1+E2$ mixed transitions.

Different hypotheses were tested.

(i) With only one parameter $M_1$ (no band mixing), $\chi^2/f=13.02/9=1.44$ (for $f=9$ degrees of freedom), the relation

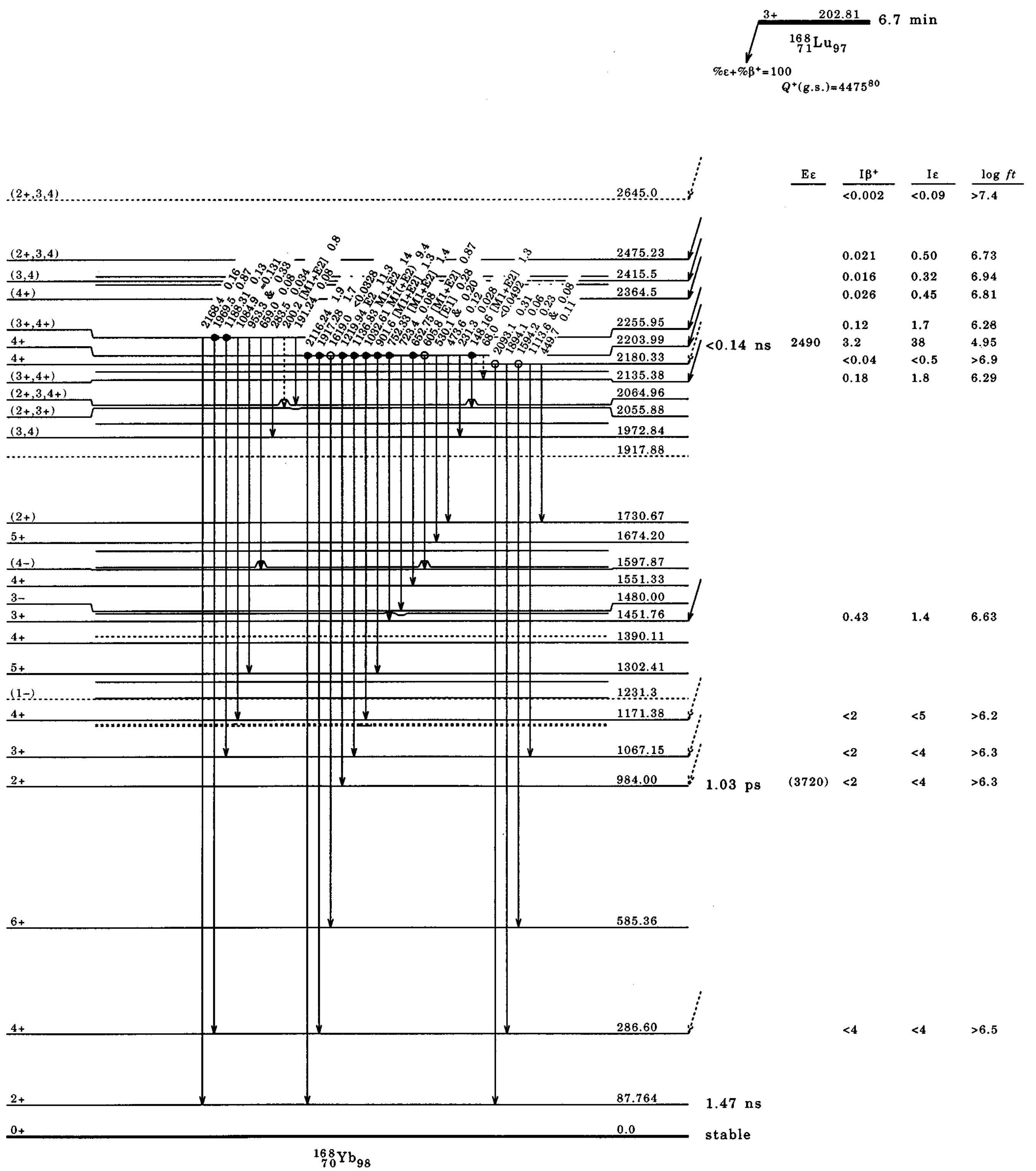


FIG. 3. $\beta$ decay scheme (continued).

accounts for a satisfactory description in the pure unmixed band model with

$$\sqrt{2}M_1=(0.359\pm 0.005)e\ \mathrm{b}.$$

(ii) With the introduction of the $M_2$ parameter, we have

$$\sqrt{2}M_1=(0.368\pm 0.010)e\ \mathrm{b},$$

$$\sqrt{2}M_2=(1.6\pm 1.6)\times 10^{-3}e\ \mathrm{b}.$$

$M_2$ is not significantly different from zero (Fig. 7), and worse, $\chi^2/f=11.89/8=1.49$ is increasing, so the result must be discarded.

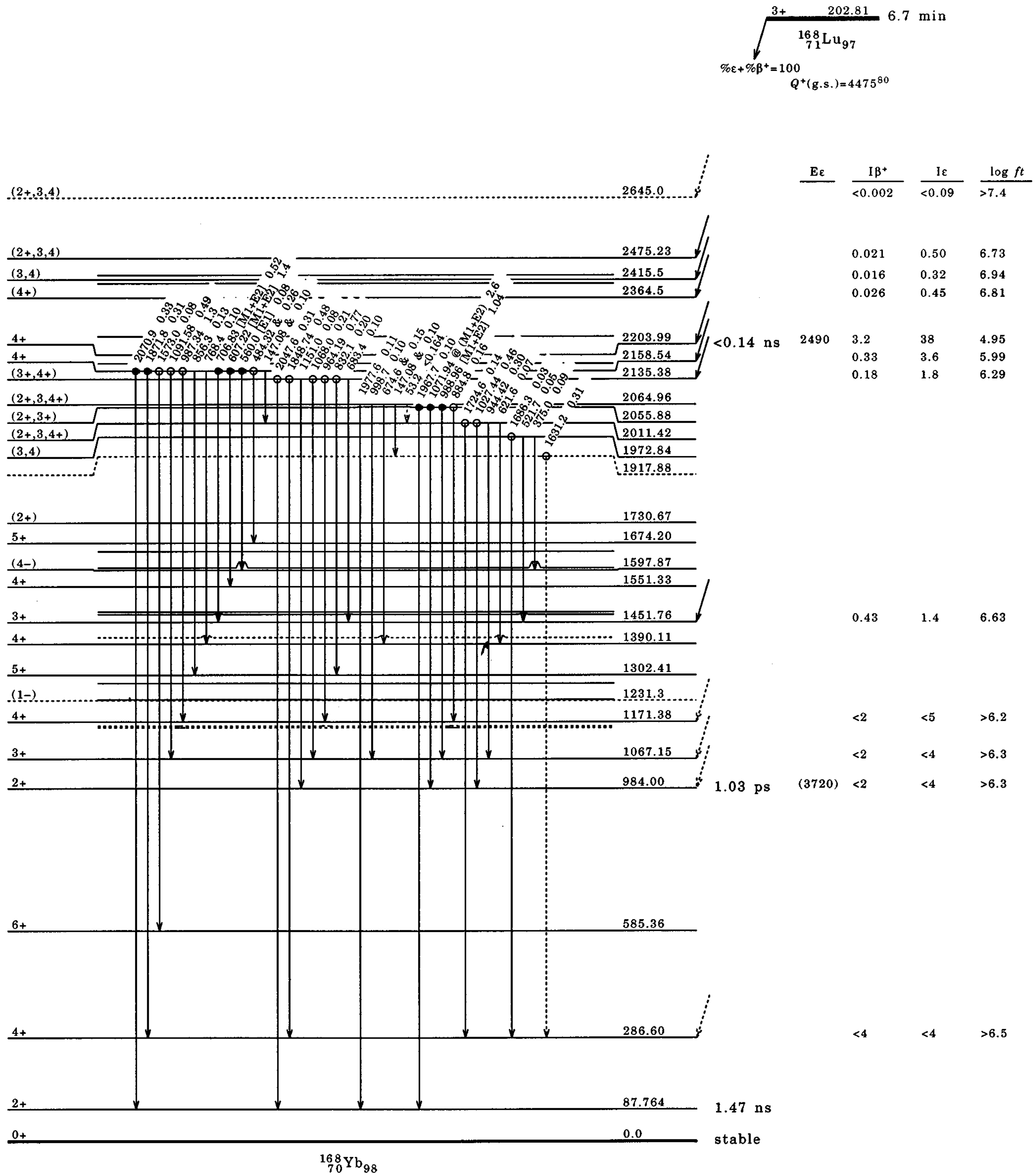


FIG. 4. $\beta$ decay scheme (continued).

(iii) However, a closer look at the figure shows that the disagreement may come mostly from the two transitions $4\rightarrow 2$ and $4\rightarrow 6$, observed in this work for the first time, having a lower intensity than expected. We might ask if this discrepancy is a real effect or is due to the high uncertainty of the measurement. If the two points are omitted, $\chi^2/f=5.80/6=0.96$ and

$$\sqrt{2}M_1=(0.406\pm 0.015)e\text{ b},$$

$$\sqrt{2}M_2=(7.9\pm 2.5)\times 10^{-3}e\text{ b}.$$

The result seems quite correct, but we have to note that many hypotheses were introduced: in addition to the one that $\Delta I$

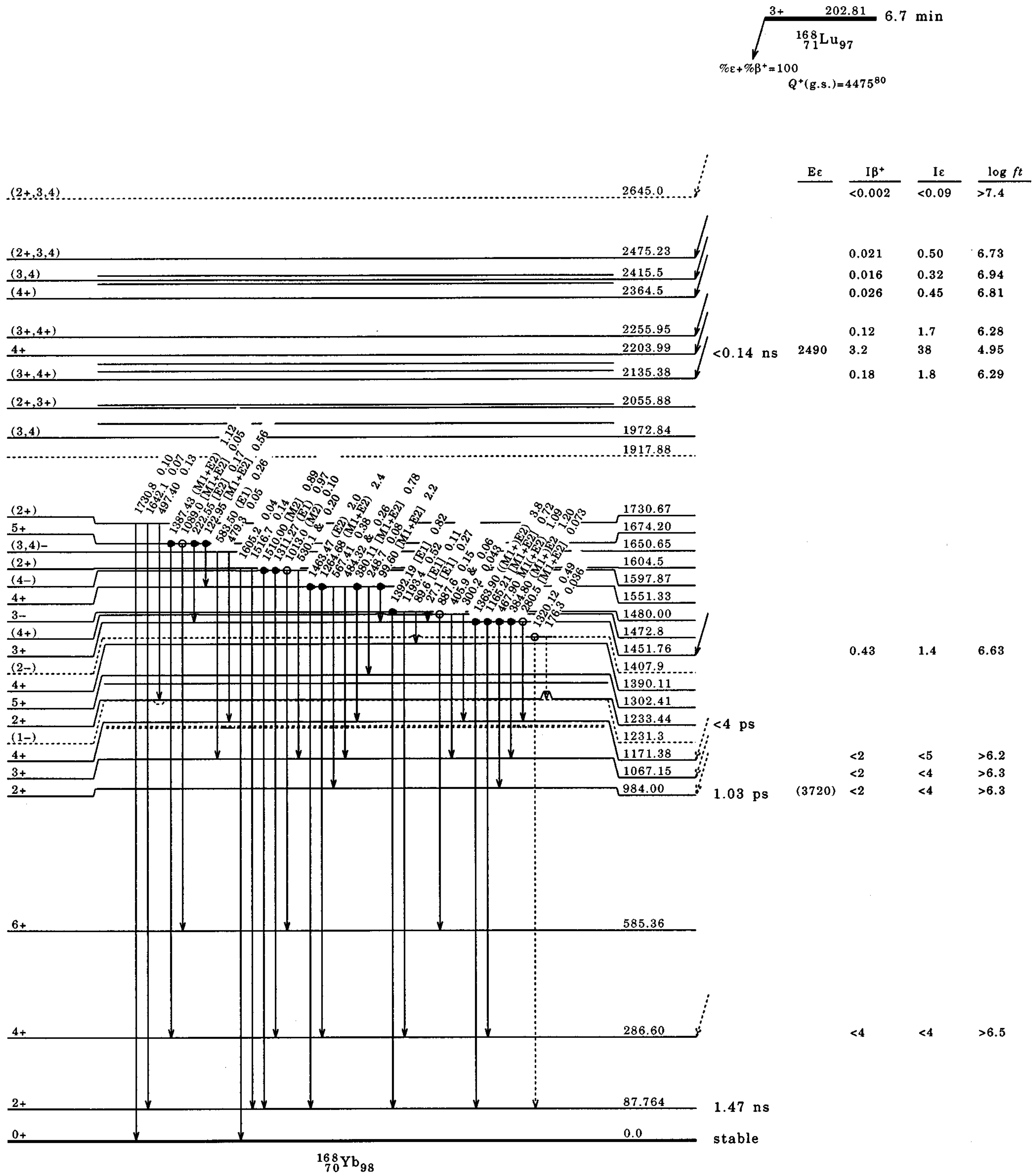


FIG. 5. $\beta$ decay scheme (continued).

$=1$ transitions be pure $E2$, we introduced arbitrary normalizations, to the values given by the pure rotational model, for transitions issued from $3^+$ and $5^+$ levels.

(iv) A more general formula was also proposed in Ref. [16], accounting for a difference of quadrupole moments between the two bands, but it does not supply any improvement in our situation, according to the preceding remarks.

Therefore, we may conclude that probably the $M1$ mixing is underestimated; the agreement in omitting the new experimental points may be accidental; the bare unmixed rotational model is still a good approximation.

### B. Unperturbed treatment: Alaga's rule

From the present accuracy of the experimental data we assume that Alaga's rule may be applied and we analyze our

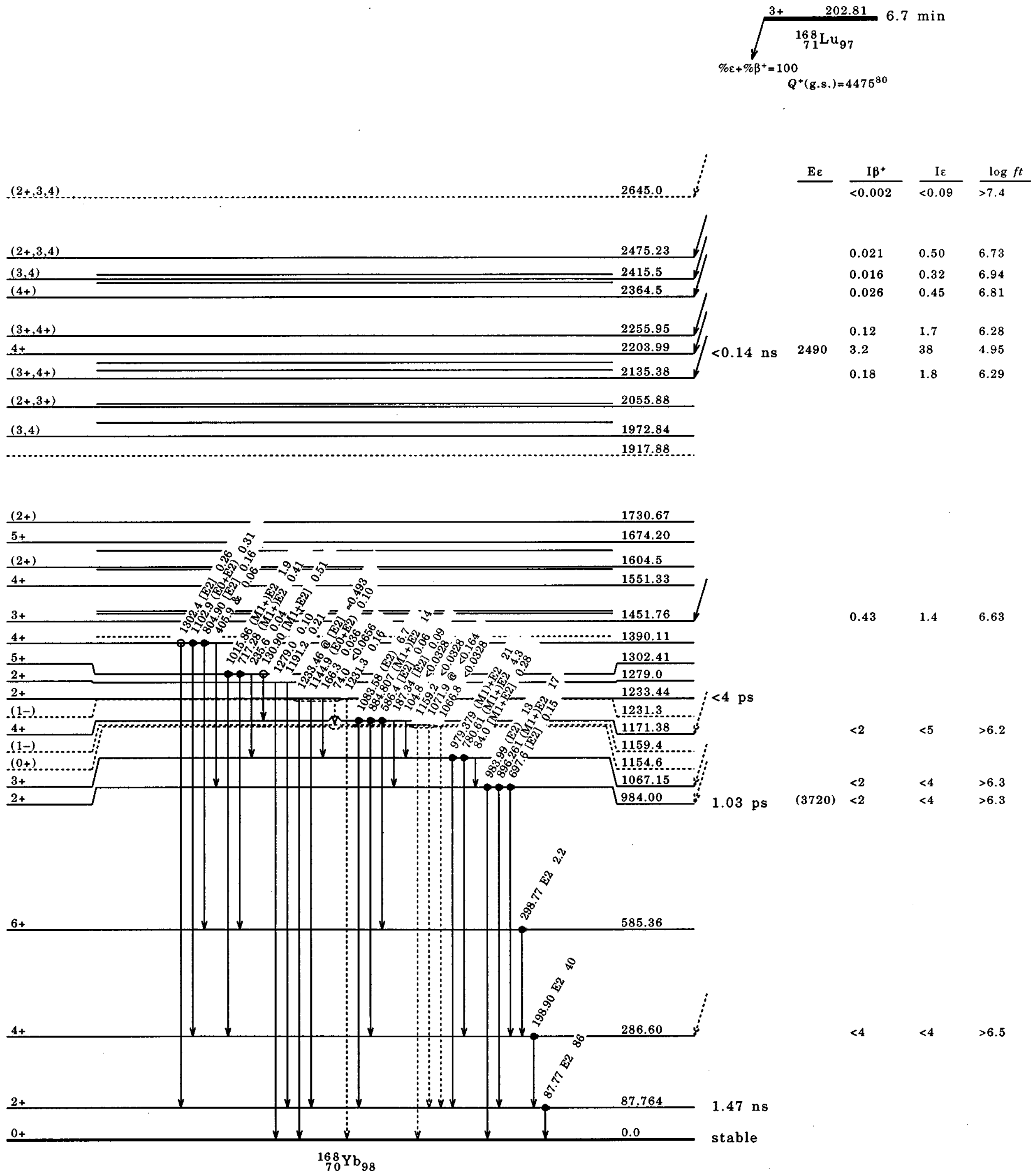

FIG. 6. $\beta$ decay scheme (continued).

data in the framework of the pure rotational model without mixing. We consider the unperturbed reduced probability ratios for the $\gamma$-to-ground band transitions. For the $I^{\pi}K=2^{+}2$ level at 984.0 keV the theoretical ratio will be

$$B(E2;22\rightarrow40)/B(E2;22\rightarrow00)=5/70=7.14\times10^{-2},$$

which compares well with the experimental ratio $(6.7\pm2.1)\times10^{-2}$. The comparison in Table III of the theoretical and experimental values supports the hypothesis that a significative $M1$ mixing be present in $\Delta I=1$ transitions. Rotational $(\Delta K=2)$ band mixing would not appear sufficient to explain the experimental intensities, so $K$ may not be a good quantum number.

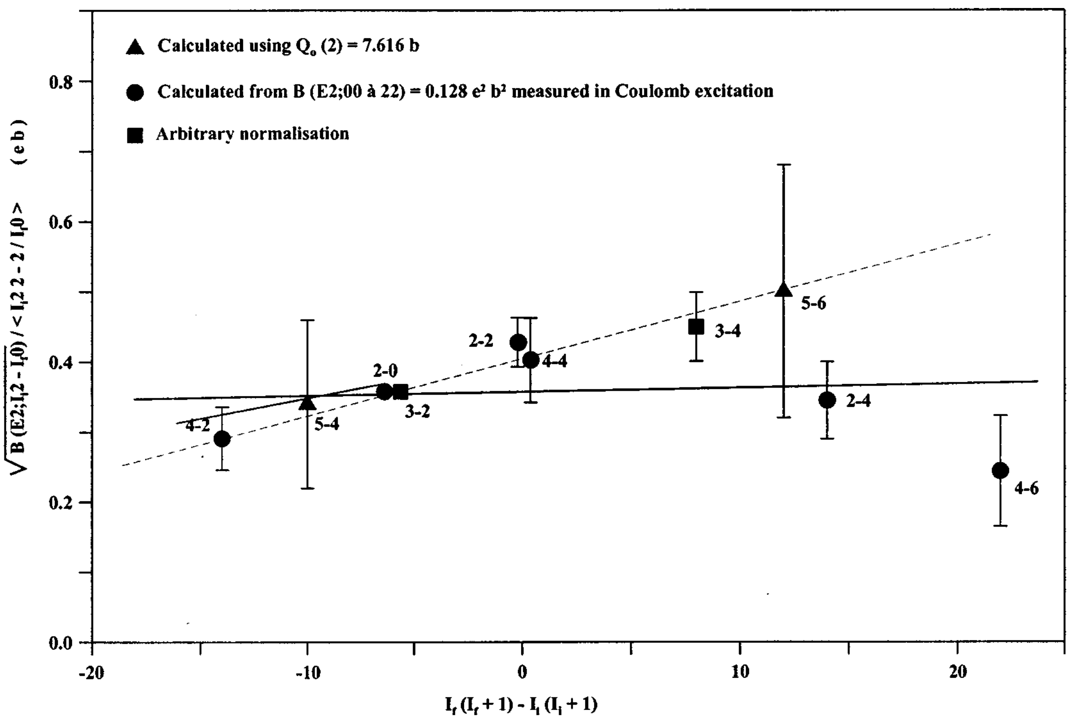


FIG. 7. Mikhailov's plot. The full horizontal line $y=0.358$ is the fit to ten points and the dashed line $y=0.406+0.0079x$ is the fit where the two points farthest to the right are omitted.

### C. Particle-hole levels

The structure of the levels directly populated in the decay of $^{168m}$Lu may be considered as best described by particle-hole configurations, lying above the pairing gap. The values of $\log ft<7$ favor allowed or at most first-forbidden transitions, so the daughter must contain large amplitude components of these permitted configurations. The parent was explained as a two-quasiparticle configuration $\{\pi 1/2^-[541]+\nu 5/2^-[523]\}_{3^+}$. The only au transition expected, and already observed in this region, was $\pi 7/2^-[523]\leftrightarrow\nu 5/2^-[523]$ with $\log ft\approx 4.7$ (see, e.g., pg. 307 in Ref. [1]). Two levels are mainly excited by $\epsilon+\beta$ decay in $^{168}$Yb: a ($J^\pi=4^+$) 2204.0-keV level and a ($J^\pi=3^+$) 2428.0-keV level with $\log ft\approx 5(4.95\pm 0.09$ for the $4^+$ level). They must own a main component of the particle-hole configuration $\{\pi 1/2^-[541]\pm\pi^{-1}7/2^-[523]\}_{3^+,4^+}$. Disregarding unessential pairing factors (see, e.g., [23], p. 215) this component represents $>56\%$ of the total configuration intensity. Actually, the identification of the level at 2428.0 keV was proposed mainly on the highly probable existence of a 24-keV transition, mostly electron converted, to the 2404.9-keV level (which otherwise might be the $3^+$ partner of the particle-hole spin-flip coupling). It may be noticed that according to Gallagher's rule [18] the lowest level of the multiplet should have $I=4(\Sigma=0)$ as proposed.

TABLE III. Analysis of branching ratios involving interband transitions between the g.s. and the $\gamma$-vibrational bands in $^{168}$Yb.

| Transition $(IK\rightarrow I'K')$ | $B(E2)$ ratio (theoretical) | $B(E2)$ ratio (experimental) |
|---|---|---|
| $(22\rightarrow 40)/(22\rightarrow 00)$ | $7.14\times 10^{-2}$ | $6.7(21)\times 10^{-2}$ |
| $(22\rightarrow 20)/(22\rightarrow 00)$ | 1.43 | 2.0(3) [a] |
| $(32\rightarrow 40)/(32\rightarrow 20)$ | 0.400 | 0.63(14) [a] |
| $(42\rightarrow 60)/(42\rightarrow 20)$ | 0.254 | 0.18(11) |
| $(42\rightarrow 40)/(42\rightarrow 20)$ | 2.945 | 5.7(13) [a] |
| $(52\rightarrow 40)/(52\rightarrow 40)$ | 0.571 | 1.2(3) [a] |

[a]Pure $E2$ transition hypothesis.

The level at 2404.9 keV may be proposed to own a main component of the particle-hole configuration $\{\pi 1/2^-[541]+\pi^{-1}5/2^-[532]\}_{3^+}$ which must lie close in energy. In this case the 201-keV (and 24-keV) transition is an allowed ($\Delta K=1$) $M1$ transition $\pi 5/2^-[532]\rightarrow\pi 7/2^-[523]$. The Weisskopf estimate for this reduced transition probability gives $B_W(M1)=1.79\mu_N$ ($\mu_N=e\hbar/2Mc$), and a theoretical calculation [19] in the framework of the Nilsson model [20], with realistic effective charge ($e_p=0.6$), gives $B(M1)=1.861\mu_N$. The two states $\pi 7/2^-[523]$ and $\pi 5/2^-[532]$ are issued from the same main shell $\pi h_{11/2}$.

Some qualitative indications may be drawn from the Nilsson model [20]. Configurations issued from the same shell model orbital, differing only for one longitudinal oscillator, must be in a first approximation at excitation energies differing from $\Delta\epsilon\sim\hbar\omega_0\delta$. The $\pi 5/2^-[532]$ and $\pi 7/2^-[523]$ orbitals are ordered in increasing excitation energy. Experimentally the mean excitation energy of the multiplet $\overline{E}(\pi 7/2^{-}[523]) = \Sigma_J (2J+1) E_J / \Sigma_J (2J+1)$ is 2302 keV, with the experimental values of the 2204.0-keV ($4^+$) and 2428.0-keV ($3^+$) spin-flip doublet. If the 2404.9-keV ($3^+$) have to be identified as the 5/2 low energy partner, the high energy ($2^+$) member may be proposed at 2475.2 keV and fed in the decay with $\log ft = 6.7$, so with an allowed hindered ($\Delta N = 0, \Delta n_z = \Delta\Lambda = 1$) transition. The partner ($3^+$) at 2404 keV must be fed with the same strength (log *ft*), which implies a feeding $\approx 0.5\%$; this could be allowed by the experimental data. For this doublet $\overline{E}(\pi 5/2^{-}[532]) = 2434$ keV, giving 132 keV for the deformed oscillator subshell separation, which is a reasonable value.

One may ask if other configurations may be identified. A rotational bandhead $3^+$ at 1451.8 keV has already been proposed in $^{168}$Yb [5] and confirmed in this work. We suggest its identification with the $\{\pi 7/2^+[404] - \pi^{-1} 1/2^+[411]\}_{3+}(\Sigma = 0)$ particle-hole configuration, which lies just under the pairing gap, and may be favored by residual interactions.

### D. Other levels

Negative-parity bands are less known in $^{168}$Yb: they are expected to be present as $K = 0^- - 3^-$ highly Coriolis perturbed bands. They are well known in the near $^{168}$Er nucleus [21,22], where all four bands were observed. In the present work some negative-parity states were weakly excited (e.g., at 1159.9, 1231.3, 1407.9, 1480.0, 1587.9, and 1650.6 keV), but their knowledge is not sufficiently established for a clear band identification. Theoretical calculations have been made by Soloviev [23] and Neergard and Vogel [24] in the framework of quasiparticles coupled to anharmonic vibrations in a random phase approximation formalism, giving qualitative agreement for ($I^-; \lambda = 3, \mu = K$) states in this region. Interacting boson model ($sd + f$ bosons) calculations have also been made by Barfield *et al.* [25] for near nuclei, but with no specific application to $^{168}$Yb.

## V. CONCLUSIONS

A careful revision of the ($\epsilon + \beta^+$) decay of the doubly odd $^{168}$Lu$^m$, $T_{1/2} = 6.7$ min, isomer was given. About 60 new transitions were placed into a level scheme of 39 excited states of $^{168}$Yb. The electromagnetic transition probabilities were discussed, and a significant multipolarity mixing was suggested. Further investigation would be needed to clearly identify negative-parity states.

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